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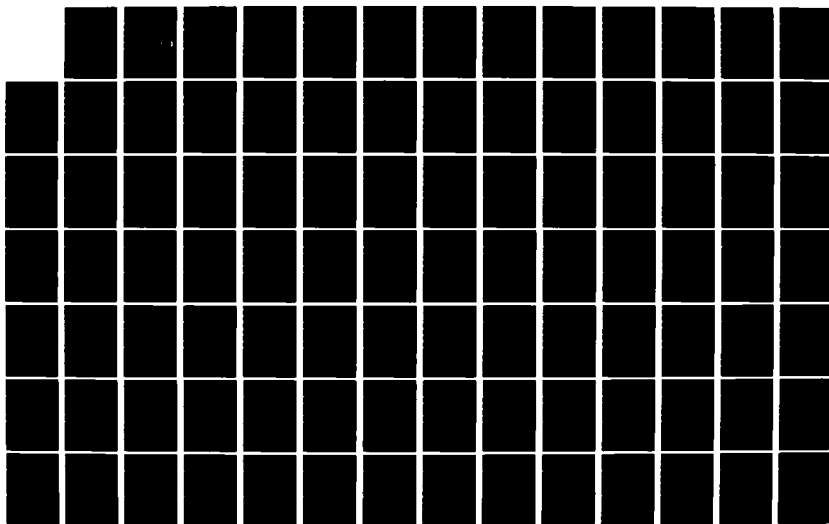
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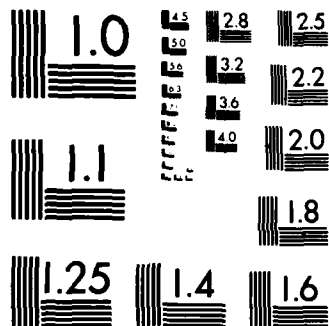
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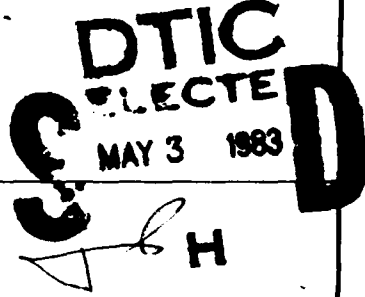




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OPTIMIZATION OF  
LONG RANGE MAJOR REHABILITATION  
OF AIRFIELD PAVEMENTS

BY

DAVID HENRY ARTMAN, JR.

B.S., Ohio State University, 1973  
M.S., University of Illinois, 1981

THESIS

Submitted in partial fulfillment of the requirements  
for the degree of Doctor of Philosophy in Civil Engineering  
in the Graduate College of the  
University of Illinois at Urbana-Champaign, 1983

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ABSTRACT

OPTIMIZATION OF  
LONG RANGE MAJOR REHABILITATION  
OF AIRFIELD PAVEMENTS

David Henry Artman, Jr.  
Captain, U.S. Air Force  
Doctor of Philosophy  
Department of Civil Engineering  
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The goal of this research has been to develop a methodology for managing pavement networks over prolonged analysis periods. Separate independent methods were devised for project and network level analysis, and the project level procedures were designed to provide inputs into the network level procedures. For the project level analysis, a computer code was written to use dynamic programming methods to optimally select schedule the activities (routine maintenance, reconstruction, and overlays) over the analysis period (20 years), by maximizing the structural performance [area under the utility weighted Pavement Condition Index (PCI) versus time curve]. At the network level, the mathematical representation of choosing those projects that maximize the sum of the user value weighted structural performance of each project, is a zero-one integer linear programming model. Projects are selected using Toyoda's heuristic (each related to a specific feature) that maximizes the objective function with pre-established constraints (network funding limit, etc.). At several funding levels, and a series of management information reports are generated. With these reports, the consequences of selected network funding levels can

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quantitatively be compared. In addition, an estimate of an appropriate level of funding for the entire system can be made. The simple example shows a substantial difference between a manually developed network program and a program developed with the procedures developed in this research and an application to an existing Air Force base was presented.

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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THE DEGREE OF DOCTOR OF PHILOSOPHY

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from around the world and at the same time be in close proximity with another MAJCOM's airfields.

The decision structure from which pavement management planning is developed is an integral part of the base, command, and Headquarters Air Force organization. While it is the responsibility of each individual airfield (base) to develop a pavement management plan, it is still responsible to its MAJCOM and ultimately the Air Force Headquarters for authority and resources to execute it.

### 1.3 Long Range Planning in Pavement Management

In maintaining an airfield, base pavement engineers must plan, program, and budget for maintenance or rehabilitative activities many years in advance. These engineers also seek assurance that their plans provide the "best" available airfield for the expended money. Not only the needs of the using aircraft but also the series of rehabilitative activities as a whole must be taken into consideration. Only then can the pavement engineers effectively manage the Air Force pavement system.

Static, "What do I do now?" approaches to pavement management lead to neglect, waste and abuse of the airfield pavement system. Consideration of the future as well as existing status of all airfield pavement sections and projected user needs must be undertaken. Techniques for developing long range management plans must provide

alternatives for decision makers to choose from, and must be sufficiently flexible to allow input from these decision makers, to adequately convey the consequences for making a decision, and should ideally direct the plan development towards a goal or set of goals established by the engineers themselves.

#### 1.4 Research Objectives

The pavement management needs of the Air Force pavement engineers led to the effort contracted to the Corps of Engineers' Construction Engineering Research Laboratory (CERL) in the early 1970's. As a result, CERL has produced several pavement management aids (Pavement Condition Index [PCI], Airfield Pavement Management System [APMS], and PAVER) (7,8,9). These systems provide Air Force pavement engineers with data storage and retrieval, data manipulation and data presentation capabilities.

Yet these systems still constrain the pavement engineers to only working in the present. The designing and comparing of pavement maintenance and rehabilitation alternatives remain directed at the present condition of the pavement. In order to determine a "best" plan for pavements for the next twenty years, the engineers still have to rely on engineering judgement and experience. The current systems do not help the engineers select and schedule pavement related procedures (overlays, reconstruction, etc.) over a period of time (say 20 years).

These existing techniques do not incorporate optimization procedures. Furthermore there is not currently a way to objectively compare one comprehensive plan versus another.

Not only are the long range planning capabilities limited to individual decision making for each pavement section, coordination is lacking to optimize individual long range plans at the network level (an entire airfield or group of airfields). Pavement engineers can not now optimize the expenditure of funds for a network of pavement sections over a specified period of time.

The research described in this thesis has the following goals:

- 1) The development of a methodology to optimize the selection and timing of major rehabilitative activities over a specified period of time at a given funding level for individual pavement features (project level).
- 2) The development of a methodology to optimize the selection of these activities at the network level, also with limited funding and for a specified time period.

Simply put, develop a methodology to enable the Air Force keep pavements in the best condition possible given a limited budget. As an additional development, the methodology enables the prediction of the performance of the long range plan as it affects the whole network.

### 1.5 Research Organization

The research described herein consisted of developing a methodology to optimize the development of long range airfield pavement rehabilitative plans, writing interactive user-oriented computer programs for implementing the methodology, and an analysis of the information generated by the programs. Several operations research techniques (dynamic programming, integer programming, etc.) were used to model the decision process associated with long range planning and resource allocation. An application of the developed computer codes and the associated analysis is presented using an existing Air Force base. The example is explained in detail from raw data gathering through an discussion of the results.

Chapter 2 reviews the current Air Force pavement management systems and discusses the ideas, problems, and concepts associated with using optimization in pavement management. Long range project level optimization and its related dynamic programming models are in discussed Chapters 3 and 4, while network optimization and its integer programming models are covered in Chapter 5. An application of the techniques and analysis is made for an Air Force base in Chapter 6. Finally in Chapter 7, the thesis is summarized, recomendations are made, and conclusions are presented.



## CHAPTER 2

### PAVEMENT MANAGEMENT

#### 2.1 What is Pavement Management?

Pavement management is a decision process supporting the construction, maintenance, and use of aircraft and motor vehicle pavements. motor vehicles. According to the Federal Highway Administration (FHWA), pavement management is:

"the process of coordinating and controlling all activities related to pavements in an attempt to best utilize public funds for providing and maintaining pavements in a serviceable condition on a continuing basis. Effective pavement management, by necessity, involves the utilization of feedback of information on pavement performance, pavement maintenance, pavement rehabilitation activities, and the cost of providing and maintaining pavements" (10).

The frame work or mechanism for pavement management is called the pavement management system (PMS).

"A PMS is a set of tools or methods that assist decision-makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time. The function of a PMS is to improve the efficiency of decision-making, expand its scope, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization" (11).

In general pavement management activities can be characterized at two levels, network and project. Network level pavement management enables the selection of the best set of projects from many sections of the pavement system (i.e., state highway system, airfield or group of airfields). At the project level, decisions center upon specific sections of pavement.

## 2.2 What is Optimization?

The word optimization is rapidly becoming widely used in pavement management. A clear understanding of optimization, as it applies to pavement management, is essential before its potential can be fully realized. The discipline of Operations Research (OR) is oriented towards finding best solutions to problems. This search for best solutions doesn't merely mean improving the status quo, but finding the best possible solutions to problems. Usually, in order to obtain solutions, operations research entails mathematical modeling of the decision process. But before modeling can be undertaken, there must be a clear understanding of the variables and constraints entering into the decision process. Additionally, and equally important, the goals or objectives of the decision process must also be understood. Only on the basis of a clear understanding of the relevant variables, constraints, and objectives, can an adequate mathematical model of the decision process be constructed.

A feasible solution to a problem is one that satisfies all the constraints in the problem. An optimal solution is a feasible solution that has the best value of an objective function (20). An objective function is a mathematical representation of the criteria for judging alternative feasible solutions. Examples of objective functions (sometimes referred to as "benefits") include minimize expended money, maximize performance, minimize the number of people used, maximize total

traffic volume, etc. In any case, objective functions are used to measure how well a specific feasible solution satisfied the constraints. Only after all feasible solutions are explicitly or implicitly evaluated can the optimal (best) solution be identified.

Since it is not always possible to define, let alone understand all the variables that enter into a problem, the optimal solution to a mathematical model should be qualified as representing the best solution when considering only those variables, constraints, objectives, and structure of the defined model.

### 2.3 Optimization in Pavement Management

Developments over the last decade have enabled quantification of the major variables associated with pavement management (distress, performance, etc). Due to inflated construction costs and reduced pavement maintenance budgets, developing optimal decision policies has been emphasized. Although the complexity of the pavement management process precludes manual solutions, the introduction of OR techniques and computers has enabled effective analysis. It is now possible for engineers to develop not only feasible, but also optimal solutions to pavement management problems.

Since pavement engineers seek to provide the best possible pavement within the framework of many constraints, pavement management is a prime

area for using optimization techniques. The important attributes of the pavement system (cost, condition, performance, effectiveness, etc.) can be represented by quantitative methods. Using these models, pavement engineers can develop optimal plans at both the project and network levels of pavement management.

### 2.3.1 Project Level Pavement Management

This level of pavement management entails developing rehabilitative strategies for specific sections of pavement. Given a feasible set of alternative activities (routine maintenance, reconstruction and overlay) these activities should be scheduled in a way that is best with respect to both cost and benefit associated with the pavement section. Using OR techniques, alternative activity schedules can be developed for various levels of funding. For a specific level of funding, there is at least one schedule of the alternative actions that provides the maximum benefit to the pavement section. OR techniques can identify the best alternatives.

### 2.3.2 Network Level Pavement Management

In addition to project level pavement management, pavement engineers must develop a plan for allocating funds for a group of pavement sections (herein referred to as a network). The network may

represent only a few sections (less than 10) or as many as several hundred sections, and these sections may be adjacent or discontinuous. In any case, the set of projects for all pavement sections that provides the most benefit must be selected. For example, a network analysis with a hundred sections, each with three alternatives, would be difficult to manually identify the group of alternatives that give the maximum benefit. But with the aid of OR techniques, specific section alternatives can be selected in order to maximize the benefit.

### 2.3.3 Optimization Application in Long Range Planning

Pavement engineers are faced with planning not only for the present but also for the future. If only the present condition and usage of pavements were considered and if future condition and usage is ignored, it is impossible to maximize the structural performance of the pavement. In developing a schedule of rehabilitative measures over the entire analysis period (say 20 years), the consequence of scheduling an alternative in one period significantly affects the scheduling and selection of the alternatives in later periods. Additionally, each feasible combination of alternative rehabilitation techniques has consequences on the performance of the section. Therefore, when selecting and scheduling a series of rehabilitative measures, it is important to optimize the performance of a pavement section over the entire analysis period. Since the availability of funds to support pavement activities is highly variable, it is also important to carry

out the optimization assuming several different levels of funding. Because the selected project schedules include work for not only the present but also for the future, choosing optimally among these project alternatives, at the network level provides overall optimal long range planning.

#### 2.4 Optimization Approach for this Research

The optimization approach in this research is to initially develop long range major rehabilitative plans at the project level for various amounts of funding. These optimal plans for all the pavement sections are then used to develop overall long range major rehabilitative plans at the network level. Finally, the impact of various network funding levels is analyzed to develop a basis for estimating an appropriate level of network funding. The methodologies for accomplishing these tasks are presented in the following chapters of this thesis.

#### 2.5 Current Pavement Management Systems

Agencies responsible for pavement management whether local, state, or federal utilize some form of pavement management for planning, allocating budgets, assigning work schedules, etc. When the pavement system is not extensive, these functions can be handled by a few individuals. But as the size of the systems grows, so do the management

responsibilities, problems, and staff size (11).

The development of pavement management techniques has progressed from the very simple to the extremely complex, but for the purposes of discussion, four levels of sophistication will be addressed. In all cases the decisions to be made are which maintenance or rehabilitative activities are necessary and when should they be scheduled.

The first level of pavement management is in essence no management at all, that is choosing activities at random. Pavement engineers could conceivably distribute maintenance resources without any knowledge of the needs of either the pavement or user. This is a very poor pavement management system and fortunately rarely occurs.

The next level of sophistication occurs when pavement engineers inspect the pavement network within their jurisdiction and establish priorities and needs for specific sections of the network. Priorities or user requirements from either traffic composition and/or volumes are specified; needs are determined from visual distress, technical knowledge, and the previous pavement experience of the engineers. Because many pavement networks are complex, objective repeatable assessments of need are difficult. The subjective nature of these



decisions do not allow valid comparisons of alternative plans.

The third level of pavement management decision processes and assessment systems are developed to quantify the priorities and needs of a pavement structure. Objective management results, and alternatives and user needs are rationally evaluated. At this level, decisions are made at the project level and the best activities selected considering only individual sections. Making the most cost effective decisions for each pavement section for the benefit the entire network is the objective of the third level.

Today, the Air Force is primarily at this third level of sophistication. Sophisticated aids are available (computer programs such as APMS, PAVER, etc.) that allow pavement engineers to systematically develop objective alternatives for pavements (8,9). The use of computers has allowed examination of large quantities of data and detailed analyses of alternative designs for specific pavement sections. These programs use complex decision trees to establish user and pavement needs, and develop network plans.

The research in this thesis addresses a fourth level of pavement management, the use of OR techniques to develop optimal pavement management plans. At this level of pavement management, the models and procedures of the third level are assumed to be available and are incorporated into an OR analysis.

Without the use of OR techniques, pavement engineers have little chance to reach the "best" possible decisions. Application of OR techniques has been limited in current pavement management systems because of limited knowledge and only recent developments in level three management systems. The research described in this thesis uses the existing quantitative models of pavement performance and applies OR to develop decisions for both current and future maintenance and/or rehabilitation activities.

## 2.6 Operations Research Applications in Pavement Management

The agencies responsible for our highways and airfields are at various stages of incorporating pavement management. OR techniques are used in only a few of the more sophisticated systems, some of which will be addressed next.

### 2.6.1 Kentucky

The Kentucky Department of Transportation has developed methods of applying dynamic programming techniques to resurfacing decisions to optimize the allocation of expenditures over hundreds of candidate projects each year. A multistage decision process was proposed and the optimal set of projects (based on considering many pavement sections, each with several alternatives) could be selected.

Using benefit/cost ratios the results of dynamic programming generated solutions were compared to the results of current selection process. The benefit/cost ratio achieved by the current process was only 3.21 compared to the 4.22 achieved by dynamic programming methodology (19). The techniques have been demonstrated by the research section of the Department of Transportation but has yet to be implemented by the department for routine use.

#### 2.6.2 Texas

The Texas Transportation Institute has developed a Rehabilitation And Maintenance System (RAMS) for the Texas Department of Highways and Public Transportation. RAMS consists of seven computer programs, each with its own specific task. The combined and sequential use of these programs is expected to facilitate planning, cost estimation, and fund allocation at all levels of management in the Texas Department of Highways and Public Transportation.

The OR techniques used in these seven programs include: 0-1 integer linear programming, 0-1 integer non-linear programming, and dynamic programming. "The general objective of the RAMS programs is to maximize the total effectiveness of all rehabilitation and maintenance activities scheduled for the entire highway network in the state of Texas in each year of a predetermined planning period while remaining within the available budget" (15). Their programs attempt to include not only

major rehabilitation, but also many other aspects of routine maintenance in the decision process. Limitations of manhours, equipment, and material resources for the various highway districts in the state are included as part of the decision process. The system has been demonstrated and documented but has yet to be implemented on a state wide basis. Attempts are being made to implement the system in one district next year.

#### 2.6.3 Arizona

The Arizona Department of Transportation (ADOT) has over the past several years developed a network optimization system (NOS) (by contract to Woodward-Clyde Consultants) (21). NOS uses linear programming to solve for decision variables defined as the proportion of roads in the network at the beginning of a specified time period at a specified condition that will receive a specified rehabilitation action. The total unit cost of these proportions is minimized, constrained by performance standards and mathematical limitations (i.e., sum of proportions be equal to one).

"It should be noted that the basic output of the optimization model does not identify the rehabilitation action that should be applied to a specific pavement in the state. However, it is possible to do this by combining the model output with the data base system which stores road inventory data. Thus, the condition states of various pavements in each road category can be identified from the data base system and the results of the optimization model can then be used to determine the most cost-effective rehabilitation action to be applied to each pavement in the network" (21).

The Arizona system is currently being used on a fully implemented basis. The system is still being evaluated for its usefulness and validity.

#### 2.6.4 Ontario, Canada

The Ontario, Canada Ministry of Transportation and Communications has developed a pavement management system known as: Program Analysis of Rehabilitation System (PARS). The computer based model for planning pavement rehabilitation programs for highway networks is divided into two main components: financial planning and priority planning. Financial planning determines levels of funding for selected pavement performance and usage goals. The second component, priority planning,

selects projects within a fixed level of funding.

The selection and scheduling of projects for individual pavement sections is done at the network level of analysis. Linear programming models are used to optimize the selection of projects from a large set of feasible activities. The problem is formulated into a 0-1 integer linear programming model. Since the problem is so large (many decision variables) they have relaxed the 0-1 integer constraint and constrained the decision variables to be non-negative. This allows the use of normal linear programming techniques to achieve a near optimal solution to the 0-1 integer model. The PARS system is ready for use as a standard procedure in the Ministry. The system has not yet been extensively used, therefore evaluations of it are not yet available.

## 2.7 Summary

This chapter discussed the process of pavement management, the definition of optimization as used in Operations Research, and the application of optimization to pavement management. The next chapter discusses the elements of an airfield, the project level decision process, and the adaptation of dynamic programming to this decision process.

## CHAPTER 3

## LONG RANGE PROJECT LEVEL OPTIMIZATION

3.1 General

This chapter discusses the decision process used to develop long range major rehabilitative projects for individual pavement sections. The discussion includes: explanation of airfield features (pavement sections), decision process description, adaption to dynamic programming, optimization criteria, and optimization constraints.

3.2 Airfield Pavement System Features

An airfield pavement system cannot be analyzed as a single unit because of the variability present in pavement type, use, thickness, construction and maintenance history, traffic area, and condition. Therefore the airfield must be divided into units with common

characteristics called "features" (27). The important characteristics of each feature include:

- 1) Pavement type
- 2) Pavement use
- 3) Pavement thickness
- 4) Construction history
- 5) Traffic area
- 6) Pavement condition

#### 3.2.1 Pavement Type

Pavement types consist of flexible, jointed concrete, rigid overlay on rigid, nonrigid overlay on rigid, rigid on flexible, composite, and reinforced rigid pavements. A specific feature must include only one of the above types.

#### 3.2.2 Pavement Use

Airfield pavements are primarily used as runways, taxiways, or aprons. A feature must have only one of these uses. A taxiway through an apron should be classified as a different feature than the apron through which it passes.



### 3.2.3 Pavement Thickness

Pavement thickness varies greatly throughout the pavement system. Within each feature, the thickness should be a constant nominal thickness.

### 3.2.4 Construction History

On most airfields, the construction of various portions of the airfield occurred at different times, by different contractors, with different materials and techniques. The construction and maintenance history of the pavement within a single feature must be consistent.

### 3.2.5 Traffic Areas

Airfield pavements are divided into "traffic areas", based on the lateral distribution of aircraft traffic and effective gross aircraft load. Designated as "A", "B", "C", and "D", these areas represent widening traffic distribution and lessening gross loads (28). A feature must be located within a single traffic area.

### 3.2.6 Pavement Condition

Often in an feature delineated with the above criteria, a distinct portion of it is in a significantly different condition. In this case, the area should be redefined as a separate feature based on the differing pavement conditions of the two areas.

### 3.2.7 Typical Airfield Layout

Figure 3.1 is an example of a typical airfield pavement system. It shows feature delineations depicting differences in pavement type, use, thickness, and traffic areas. Construction history is annotated as in Table 3.1. Pavement condition is listed with Summary of Physical Property Data table (see example Table 3.2) under "General Condition".

This information is generally available on location at each airfield, in either an airfield pavement evaluation report or an airfield pavement condition report.

## 3.3 Project Level Definition

A long range project level rehabilitation plan represents the rehabilitative activities scheduled on a single airfield pavement feature. As alternative projects are developed for a single feature,

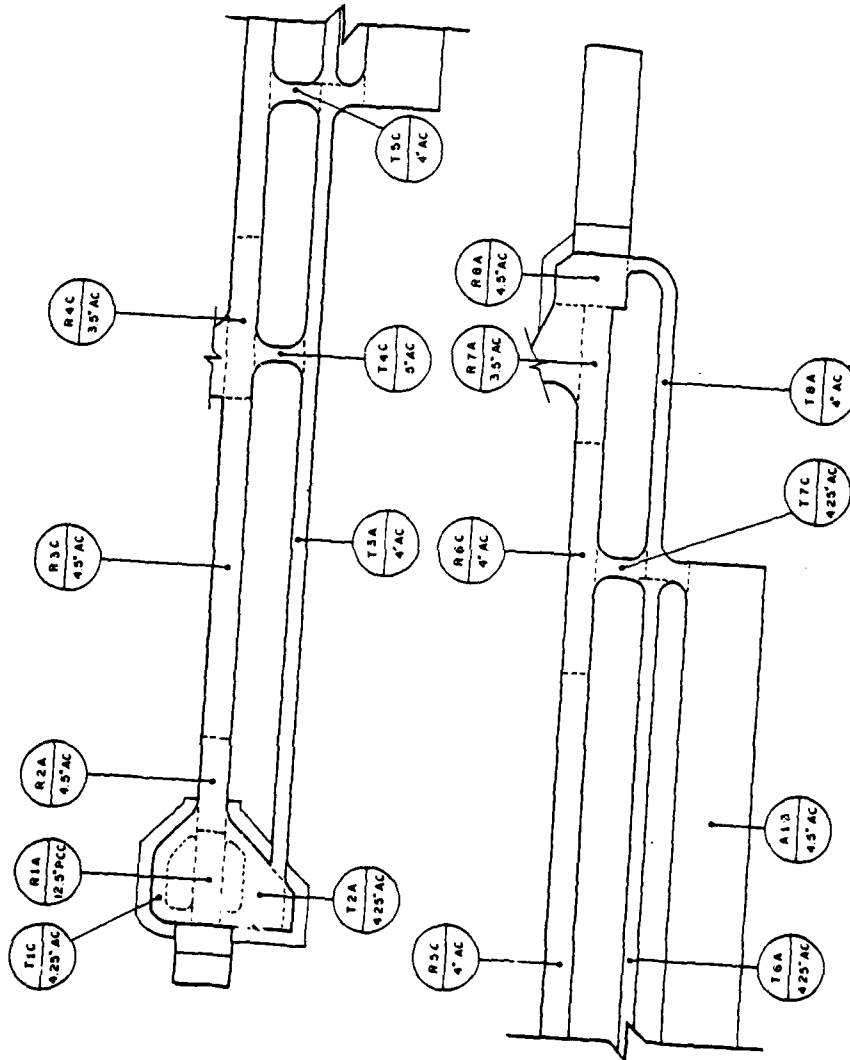


Figure 3.1 Typical Airfield Pavement Layout (27)

Table 3.1 Typical Airfield Construction History (27)

CONSTRUCTION HISTORY			
FEATURE DESCRIPTION	APPROXIMATE CONSTRUCTION PERIOD	TYPE & THICKNESS (in)	REMARKS
R1A RUNWAY, WEST END THRESHOLD STA 22+00 TO 27+00	1965/6	12.5 PCC	NOTE: SHOW DESIGN AGENCY, CONSTRUCTION AGENCY, PROJECT NUMBER AND DESIGN CATEGORY (LIGHT, MEDIUM, HEAVY) UNDER "REMARKS" COLUMN.
R2A RUNWAY, WEST END STA 27+00 TO 32+00	1965/6	4.5 AC	
R3C RUNWAY STA 32+00 TO 50+00	1965/6	4.5 AC	
R4C RUNWAY STA 50+00 TO 58+00	1970 1954	1.5 AC 2.0 AC	
R5C RUNWAY STA 58+00 TO 90+00	1970 1954	1.5 AC 2.5 AC	
R6C RUNWAY STA 90+00 TO 103+52	1970 1954	1.5 AC 2.5 AC	
R7A RUNWAY STA 103+52 TO 109+27	1970 1954	1.5 AC 2.0 AC	
R8A RUNWAY, EAST END THRESHOLD STA 109+27 TO 112+02	1965/6	4.5 AC	
T1C TAXIWAY, TURN AROUND	1965/6	4.25 AC	
T2A TAXIWAY/WASH-UP APRON	1965/6	4.25 AC	
T3A TAXIWAY, WEST PARALLEL	1965/6	4.0 AC	
T4C TAXIWAY, WEST LADDER	1965/6	5.0 AC	
T5C TAXIWAY, CENTER LADDER	1965/6	4.0 AC	
T6A TAXIWAY, CENTER PARALLEL	1970	4.25 AC	
T7C TAXIWAY, EAST LADDER	1965/6	4.25 AC	
T8A TAXIWAY, EAST PARALLEL	1965/6	4.0 AC	
A1B APRON	1965/6	4.5 AC	

AF 22000 1986

NOTE: SHOW DESIGN AGENCY, CONSTRUCTION AGENCY, PROJECT NUMBER AND DESIGN CATEGORY (LIGHT, MEDIUM, HEAVY) UNDER "REMARKS" COLUMN.



the operational interaction of th is often not taken into consideration. The project level methodology described in this thesis also does not consider these interactions, because they will be accounted for at a higher level of optimization. Simply put, project level optimization is the development of optimal alternatives for a specific feature on the airfield.

### 3.4 Project Level Decision Process

Airfield pavement engineers face a complex decision process when developing long range project level major rehabilitation plans. They must consider simultaneously the selection and scheduling of many rehabilitation activities, in addition to the interaction of two or more activities and their combined effect on the feature. The difficulty of the problem is further complicated by the inclusion of monetary, timing, and political constraints.

In this thesis the project level decision process is defined as selecting the best feasible activity at pre-established time intervals. For each feature, the decisions are: Which rehabilitation activity should be scheduled in each year of the analysis period given available funds. That is, select the set of activities that best benefit the pavement feature while at the same time not exceeding a limited budget.

The complexity of the decision process can be illustrated by considering the task of scheduling available project activities. For example, assume three activities (routine maintenance, reconstruction, and overlay) are available for scheduling at two year intervals over the next twenty years. In theory all  $3^{10}$  (59,049) possible combinations of these activities should be considered. If the list of activities is increased by two possibilities of two thicknesses of overlay, the number of possible combinations to consider increases to  $5^{10}$  (9,765,625). If these activities must be considered every year then  $5^{20}$  ( $9.54 \times 10^{13}$ ) combinations must be evaluated.

The mere scope of this decision process has previously prevented pavement engineers from considering all possibilities. Figure 3.2 depicts the components of this decision process.

### 3.5 Dynamic Programming Application

The decision process previously described can be modeled as a staged decision process and can be optimally solved using dynamic programming, a systematic procedure for determining the combination of decisions that optimizes the overall process. However, to model and solve the process, it is important to have a clear understanding of what comprises the decision variables, the objective function, and the process constraints (29).

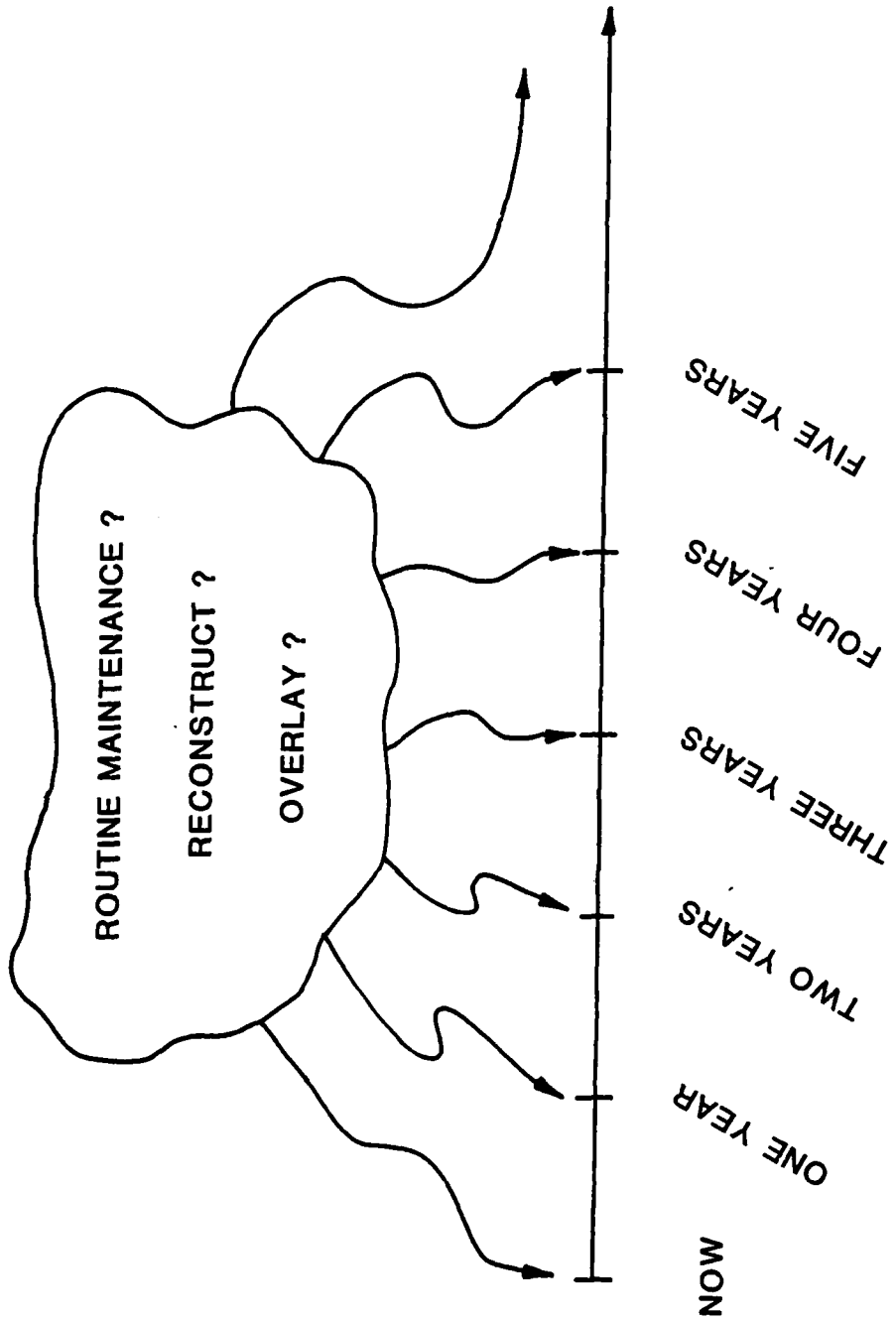


Figure 3.2 Decision Process Time Line



Decision variables are the variables in the model that can be changed, i.e. which activity to choose for each point in time. Changing the value of a decision variable (selecting another activity) changes an outcome (performance of the pavement feature).

The objective function is a measure of the effectiveness (pavement performance) of a specific set of decision variables (rehabilitative activities). This function is optimized i.e., the set of decision variables (activities) is selected that optimize the objective function (maximize the pavement performance).

Constraints are mathematical expressions representing conditions that the decision variables must satisfy. For example, the total cost of a specific set of activities must be within a budget limitation, the condition of the pavement must drop below a specified limit before any activities can be selected, etc. The decision variables must satisfy these constraints as well as optimize the objective function.

With dynamic programming, pavement engineers can solve the large complex decision process of selecting the best rehabilitative activity at specific time intervals. Instead of 59,049 possible combinations to analyze (as in the previous example), the problem reduces to 90 possible combinations.

### 3.6 Criteria for Pavement Management

As previously noted, the objective function is the mathematical expression that measures the effectiveness (performance) of a specific set of decision variables (alternative rehabilitative activities). This objective function becomes the optimization criterion for the decision process.

The optimization criterion used to measure performance of a set of rehabilitative activities in this thesis is the utility weighted area under a curve defined by the pavement condition index (PCI) versus the time of the analysis period (7,27).

#### 3.6.1 Pavement Condition Index

The pavement condition index (PCI) is a numerical indicator, between 0 and 100, that reflects the structural integrity and surface operational condition of the pavement. The structural integrity is the ability of the pavement to resist fracture, distortion, and disintegration. The PCI is calculated as a function of distress type (rutting, alligator cracking, cracked slabs, etc.), distress severity (depth of rut, spalling of pieces in alligator cracking, number of slab pieces and condition of crack, etc.), and distress density (extent which distress covers sample area in percent of total area). The PCI is an objective measure that closely correlates with the judgement of a large

group of experienced pavement engineers. The method allows engineers or technicians to rate pavement condition according to a common scale of measure.

To determine the PCI, the entire pavement system (airfield) is first divided into individual elements called features, as previously defined. The airfield is then surveyed feature by feature. The PCI can be expressed mathematically as (30):

$$PCI = 100 - F(t,q) * \left[ \sum_{i=1}^p \sum_{j=1}^{m_i} a(T_i, S_j, D_{ij}) \right] \quad (3.1)$$

where:

- PCI = pavement condition index
- a( ) = deduct weighting value depending
  - on distress type  $T_i$ , level of severity  $S_j$ , and density of distress  $D_{ij}$
- i = counter for distress types
- j = counter for severity levels
- p = total number of distress types for pavement type under consideration
- $m_i$  = number of severity levels on the  $i$ th type of distress
- $F(t,q)$  = an adjustment function for
  - multiple distresses that varies with total summed deduct value (t) and number of deducts (q).

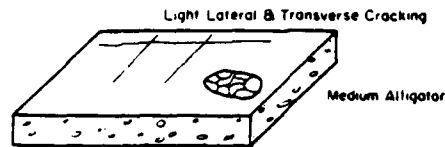
### 3.6.1.1 PCI Determination for a Feature by Survey

The steps for performing the pavement survey and determining the PCI for a pavement feature are shown in Figure 3.3 and briefly described below (30):

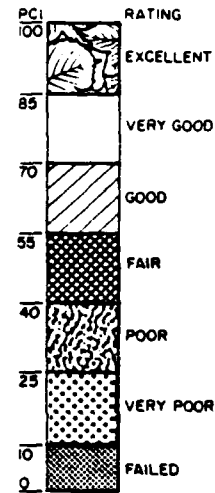
- 1) The pavement feature is first divided into sample units.  
A sample unit for concrete pavement is approximately 20 slabs;  
a sample unit for asphalt is an area of approximately 5000 square feet.
- 2) The sample units are inspected and the distress types and their severity levels and densities are recorded. It is imperative that criteria developed by Shahin, et al. (7) be used to identify and record the distress types.
- 3) For each distress type, density, and severity level within a sample unit, a deduct value is determined from an appropriate curve (7). Step 3 of Figure 3.3 provides an example of such a curve.
- 4) The total deduct value (TDV) is determined by adding all deduct values for each distress condition observed for each sample unit inspected.
- 5) A corrected deduct value (CDV) is determined from the appropriate curve (7); the CDV is based on the TDV and the number of distress conditions observed with individual deduct values over five points (see Step 5 of Figure 3.3).
- 6) The PCI for each sample unit is calculated as follows:

STEP 1: DIVIDE PAVEMENT FEATURE INTO SAMPLE UNITS

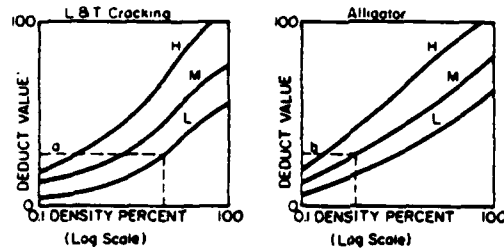
STEP 2: INSPECT SAMPLE UNITS: DETERMINE DISTRESS TYPES AND SEVERITY LEVELS AND MEASURE DENSITY.



STEP 8: DETERMINE PAVEMENT CONDITION RATING OF FEATURE

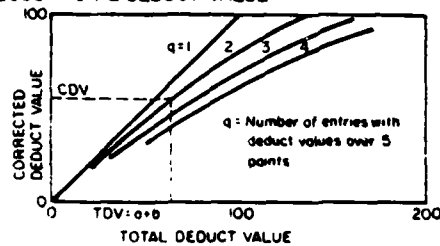


STEP 3: DETERMINE DEDUCT VALUES



STEP 4: COMPUTE TOTAL DEDUCT VALUE (TDV)  $a+b$

STEP 5: ADJUST TOTAL DEDUCT VALUE



STEP 6: COMPUTE PAVEMENT CONDITION INDEX (PCI)  $100 - CDV$  FOR EACH SAMPLE UNIT INSPECTED

STEP 7: COMPUTE PCI OF ENTIRE FEATURE (AVERAGE PCI'S OF SAMPLE UNITS)

Figure 3.3 Summary of Steps for PCI Determination (27)

$$PCI = 100 - CDV \quad (3.2)$$

- 7) The PCI of the entire feature is computed by averaging the PCIs from all the sample units inspected.
- 8) The feature's overall condition rating is determined from Figure 3.3, Step 8, giving a verbal description of the pavement's condition as a function of its PCI value.

#### 3.6.1.2 Future PCI Determination by Predictive Models

In addition to determining PCI of a feature by direct survey of the present condition, future PCIs of the feature can be reasonably predicted with regression models. These models were developed by the U.S. Army Corps of Engineers' Construction Engineering Research Laboratory (CERL) for predicting the consequences of different maintenance and repair activities (31). Several initial models were developed and are currently being improved. The models used in this research are those from the original work because they are the ones currently accepted and used by the Air Force.

##### 3.6.1.2.1 Jointed Concrete Pavement PCI Prediction Model

The following model was used to predict the PCI of a jointed concrete surfaced pavement feature:

$$\begin{aligned}
 \text{PCI} = & 100.0 - \text{AGE} * [0.01967 * \text{FAT} - 0.02408 * \text{SR} \\
 & + 0.001051 * (\text{JSL} * \text{JSS}) + 2.10579 * \text{ACOLTHK}^{-0.81} \\
 & + 0.03475 * \text{PATCH} + 2.91238 - 0.001775 * \text{FI} \\
 & - 0.04066 * \text{TEMP}]
 \end{aligned}
 \tag{3.3}$$

where:

- PCI = Pavement Condition Index at time AGE since construction or overlay with asphalt or concrete
- AGE = time since construction of slab or, if overlaid, time since overlay construction (years)
- FAT = (ratio of interior slab stress/modulus of rupture) x 100
- SR = slab replacement (percent total slabs)
- JSL = longest joint spacing (feet)
- JSS = shortest joint spacing (feet)
- ACOLTHK = thickness of overlay (inches)
- PATCH = slabs containing large patches (5 square feet), percent of total slabs, or percent area of total area patched if overlaid with asphalt
- TEMP = average annual temperature (°F)
- FI = freezing index (degree days below 32°F)

Note, when the pavement is not overlaid, the entire ACOLTHK term is eliminated because it is undefined when it is zero.

The difference between this Equation 3.3 and the original one derived by CERL is in the term ACOLTHK and therefore does not reflect the same prediction characteristics as the CERL equation. The CERL

equation had a binary (0 or 1) ACOLTHK variable. Hence it was insensitive to the various thicknesses of asphalt overlays; and the resulting predicted PCI values were not realistic. The new term was derived from a data set of 31 points and plotted as shown in Figure 3.4. The original equation was based on an average overlay thickness of 2.7 inches. The resulting coefficient of the binary term was 0.94191. The new term ACOLTHK (overlay thickness) gives the same result when 2.7 inches of overlay are used, but makes the total PCI predictive equation much more sensitive to changes to the overlay thickness. Figure 3.5 shows the sensitivity of the two equations as a function of time. Both equations are plotted for 2, 4, and 6 inches of overlay. Note the change in spread of the two equations as a function of thickness.

For this equation to be useful in the dynamic programming model, all the terms must be calculable whenever the PCI is needed in the analysis. The methods used to determine the values for these variables, are discussed in the next chapter under model development.

#### 3.6.1.2.2 Asphaltic Concrete Surfaced Pavement PCI Prediction Model

The following model was used to predict the PCI of an asphalt surfaced pavement feature (31):

$$PCI = 100 - AGE * [1.487 / \alpha_{sg} + 0.143 * AGE_{COL} + 6.56 / T_{ac} - 1.23 * \alpha_{ac}] \quad (3.4)$$



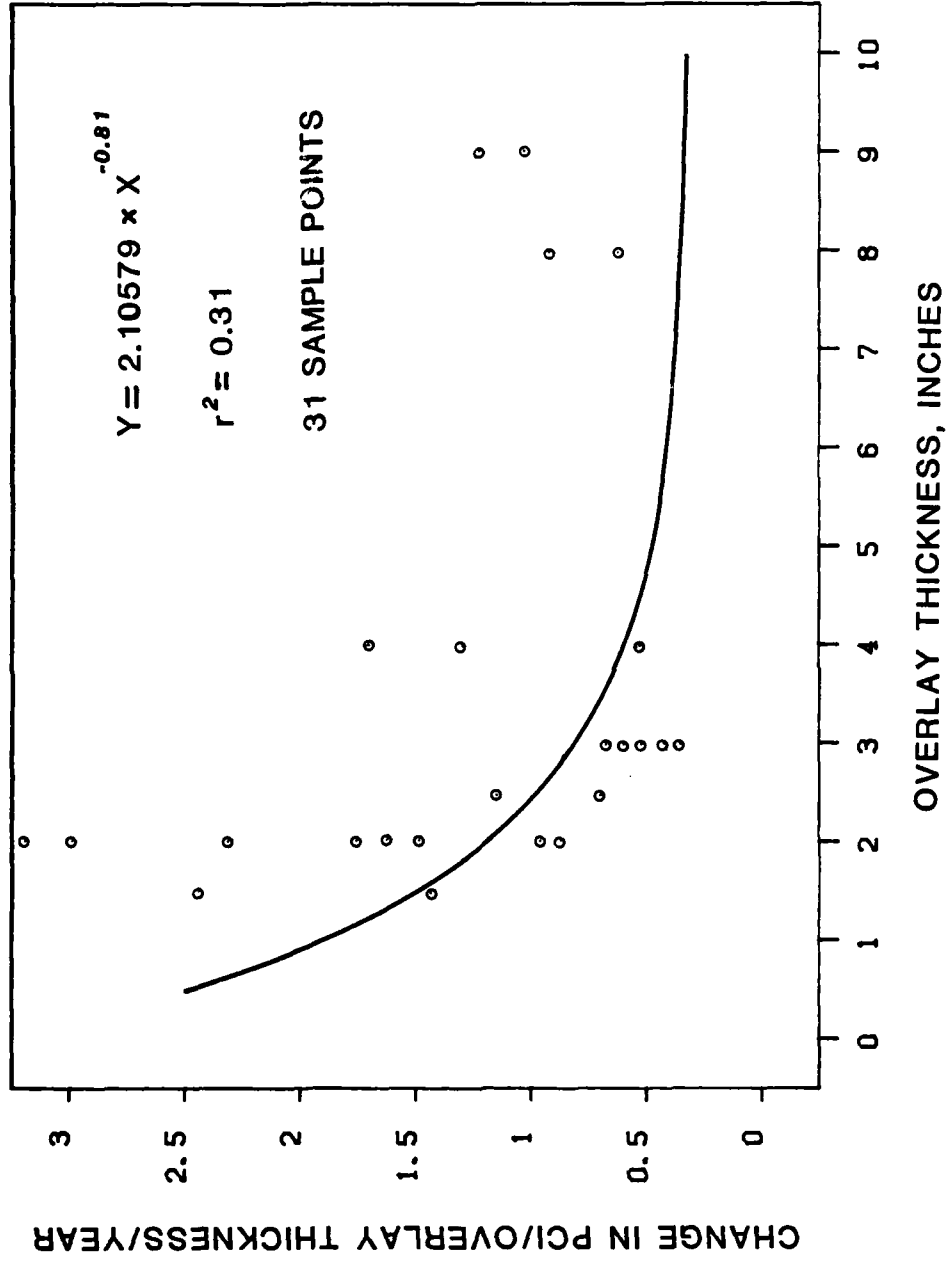


Figure 3.4 Change in PCI per Overlay Thickness per Overlay Age Versus Overlay Thickness

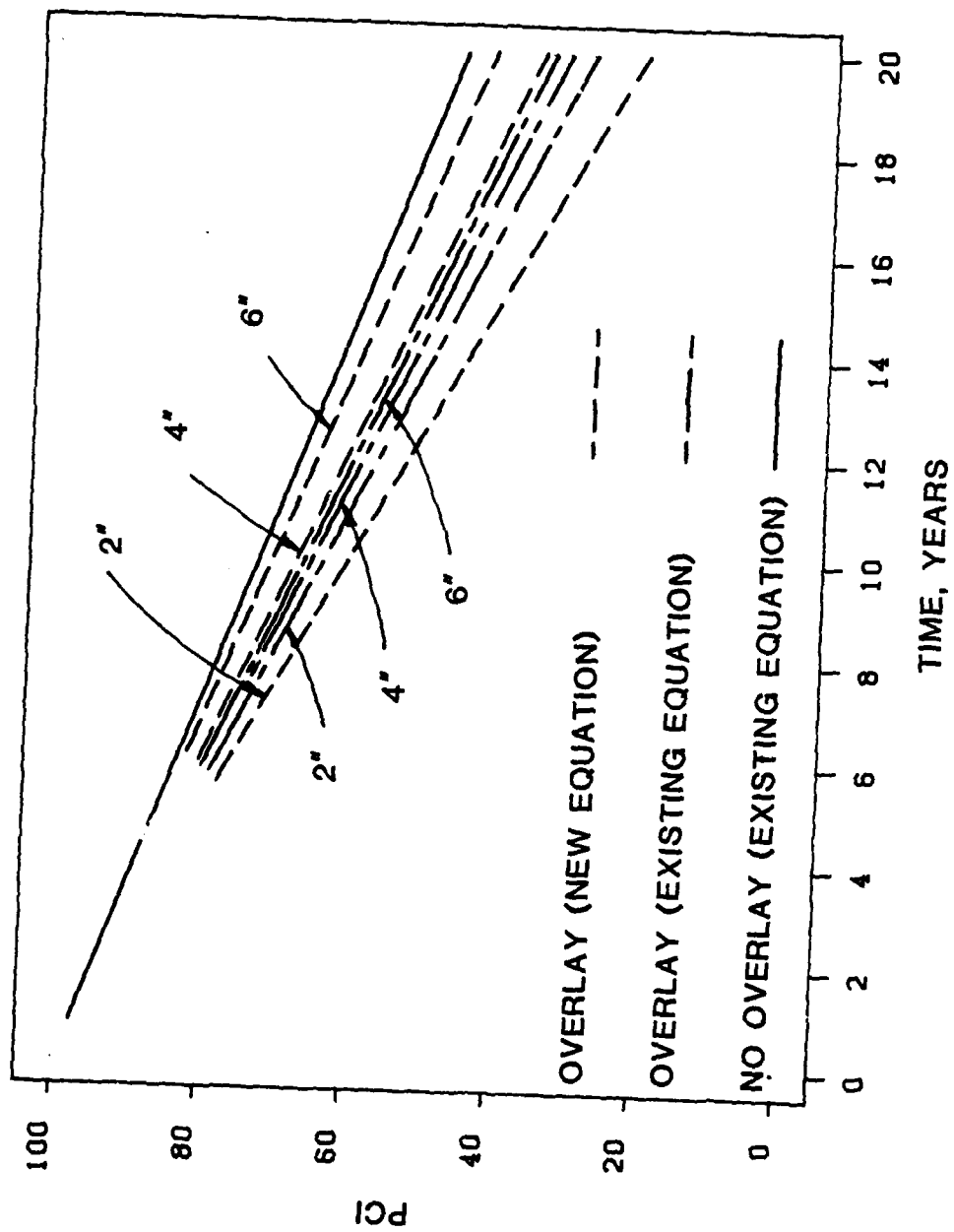


Figure 3.5 Example Showing Sensitivity of PCI Equating to Overlay Thickness

where:

AGE = age since original construction or since last overlay if the pavement has been overlaid

$\alpha_{sg}$  = load repetition factor determined at the subgrade level;  $sg$  is a function of total pavement thickness above the subgrade, subgrade CBR, and the tire contact area and tire pressure of an equivalent single wheel

AGECOL = age between the time the pavement was constructed and the time it received the last overlay; equals zero if the pavement was not overlaid

$T_{ac}$  = total asphalt thickness in inches including overlay

$\alpha_{ac}$  = load repetition factor determined at the asphalt base

The assignment of values to the terms in this equation is also discussed in the next chapter under model development.

### 3.6.2 PCI Utility

There is a difference in value to pavement engineers in improving a pavement from different levels of PCI. For example, improving the PCI of pavement from 95 to 100 is far less significant than improving another pavement from 50 to 55. This change in value for a change in PCI as a function of PCI can be modeled with utility theory. Utility is the true measure of value to pavement engineers.

Groups of experienced Air Force pavement engineers were used to establish the utility of the PCI as a function of pavement type (primary or secondary). The results of this survey are shown in Figures 3.6, 3.7 and 3.8 (32). These scales reflect PCI utility as a function of user needs and in this research user needs are accounted for in the network level analysis discussed in later chapters. Therefore a PCI utility model was extrapolated from the maintenance and repair zone versus PCI table developed by a group of experienced Air Force pavement engineers (Figure 3.9).

Using both, the utility curves (Figures 3.6, 3.7 and 3.8 and the correlation of maintenance and repair (Figure 3.9), the utility of the PCI was developed by the author for the purposes of this research (Figure 3.10). The breaks in the curve at 70 and 25 PCI represent the inclusion of major rehabilitation activities for consideration and the mandatory use of overall rehabilitation respectively. The linear mid-portion of curve closely resembles the shapes of the previously developed curves (Figures 3.6, 3.7 and 3.8).

Integrating this curve and plotting the values of the integral with respect to PCI results in Figure 3.11. This utility weighted PCI reflects the engineers' bias in relative value of PCI as a function of PCI.

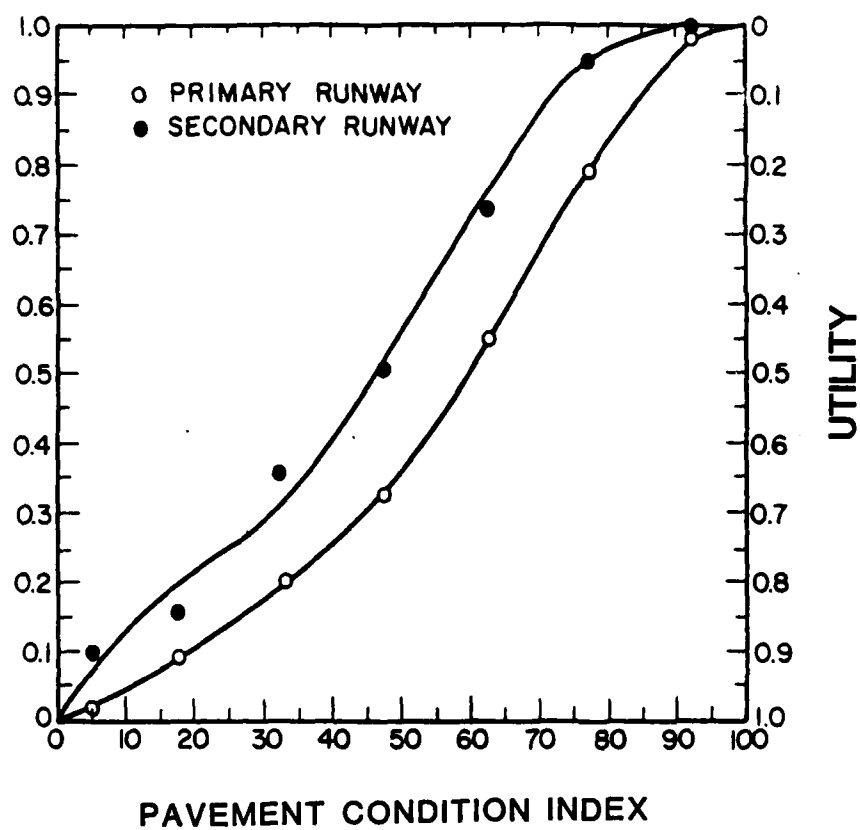


Figure 3.6 Utility Curves for Runways (32)

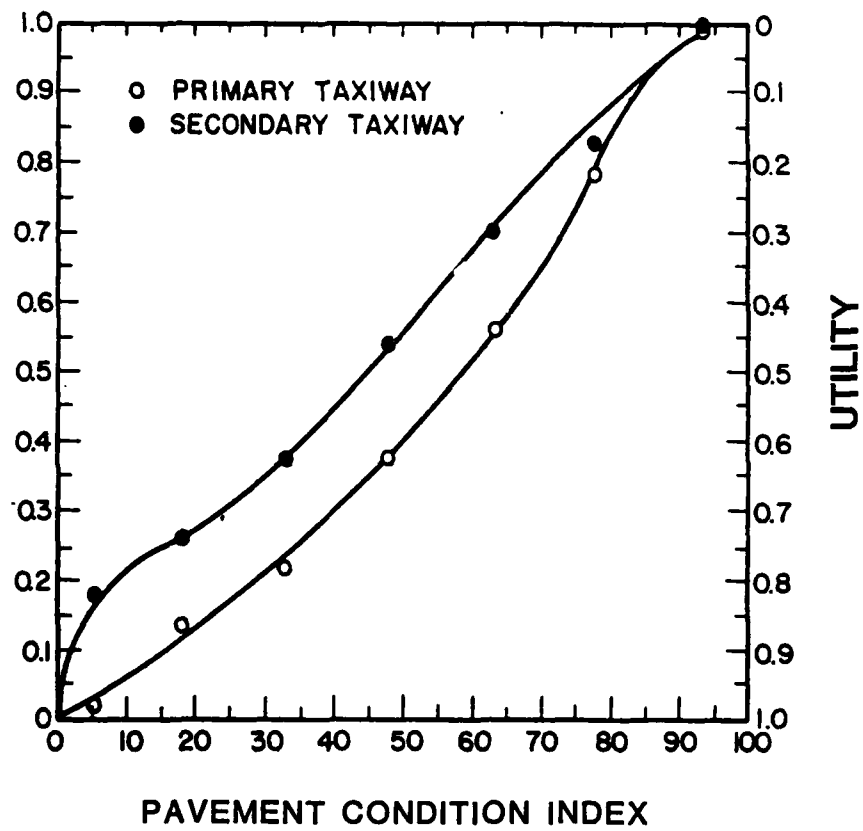


Figure 3.7 Utility Curves for Taxiways (32)

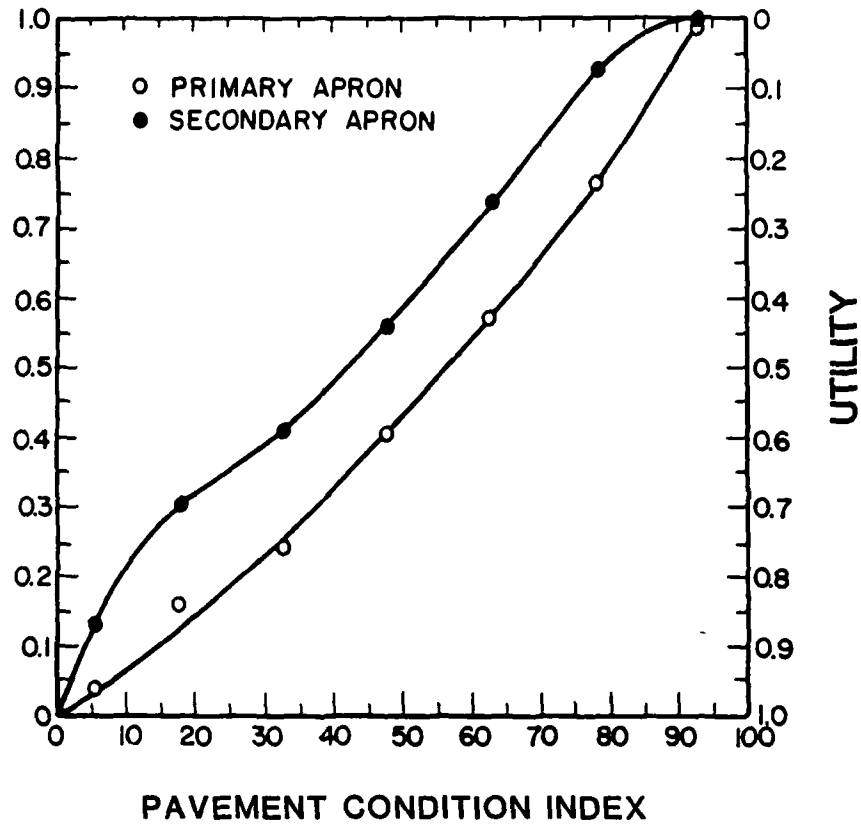


Figure 3.8 Utility Curves for Aprons (32)


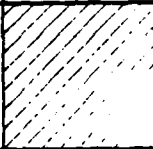
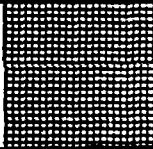
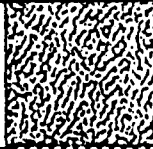
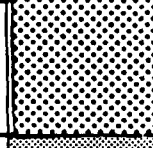
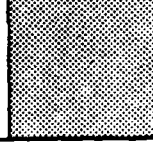
M & R ZONE	PCI		RATING
ROUTINE	100		EXCELLENT
	85		VERY GOOD
ROUTINE, MAJOR, OVERALL,	70		GOOD
	55		FAIR
MAJOR, OVERALL	40		POOR
OVERALL	25		VERY POOR
	10		FAILED
	0		

Figure 3.9 Correlation of Maintenance and Repair Zones  
and PCI and Condition Rating (32)



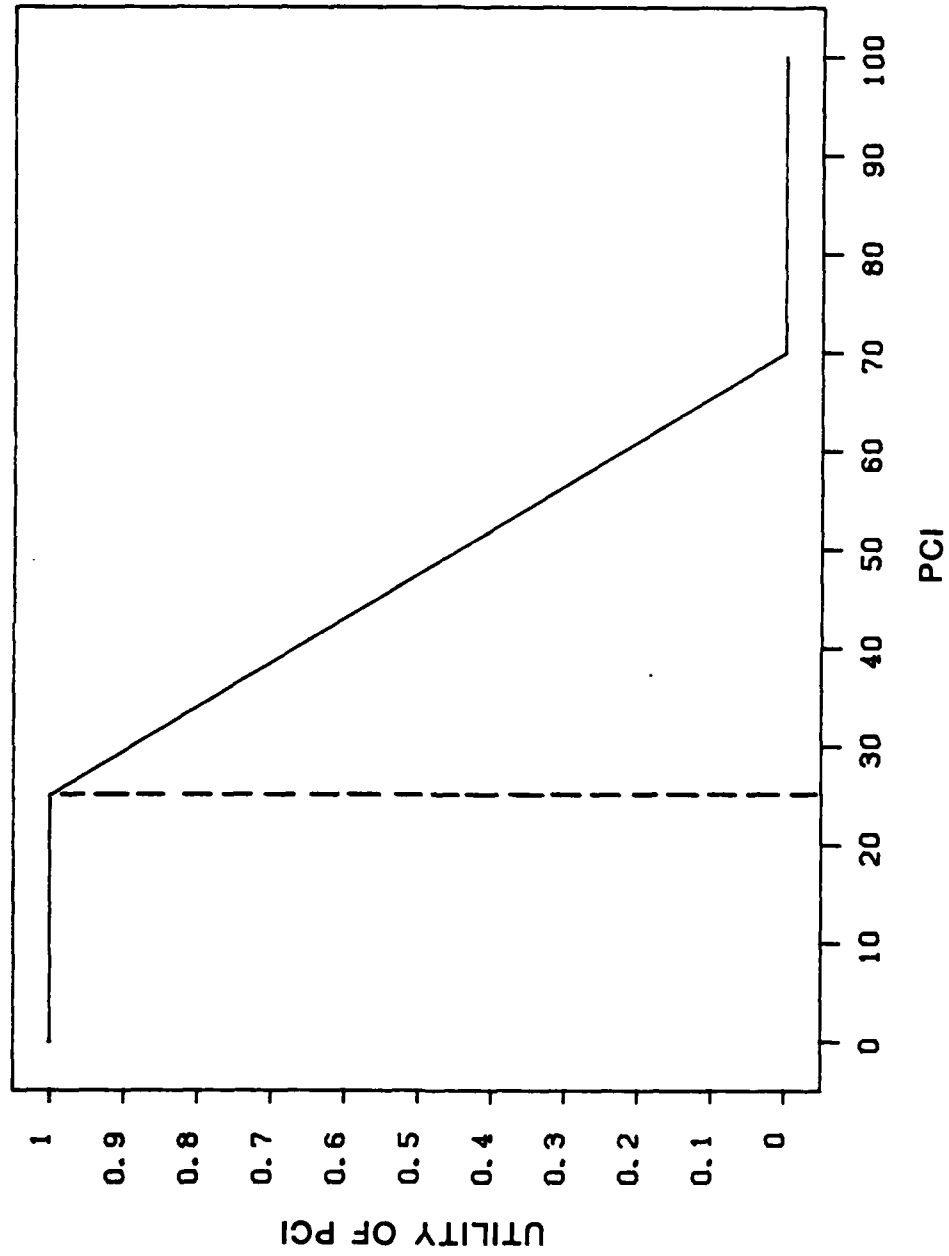


Figure 3.10 Utility of PCI Curve

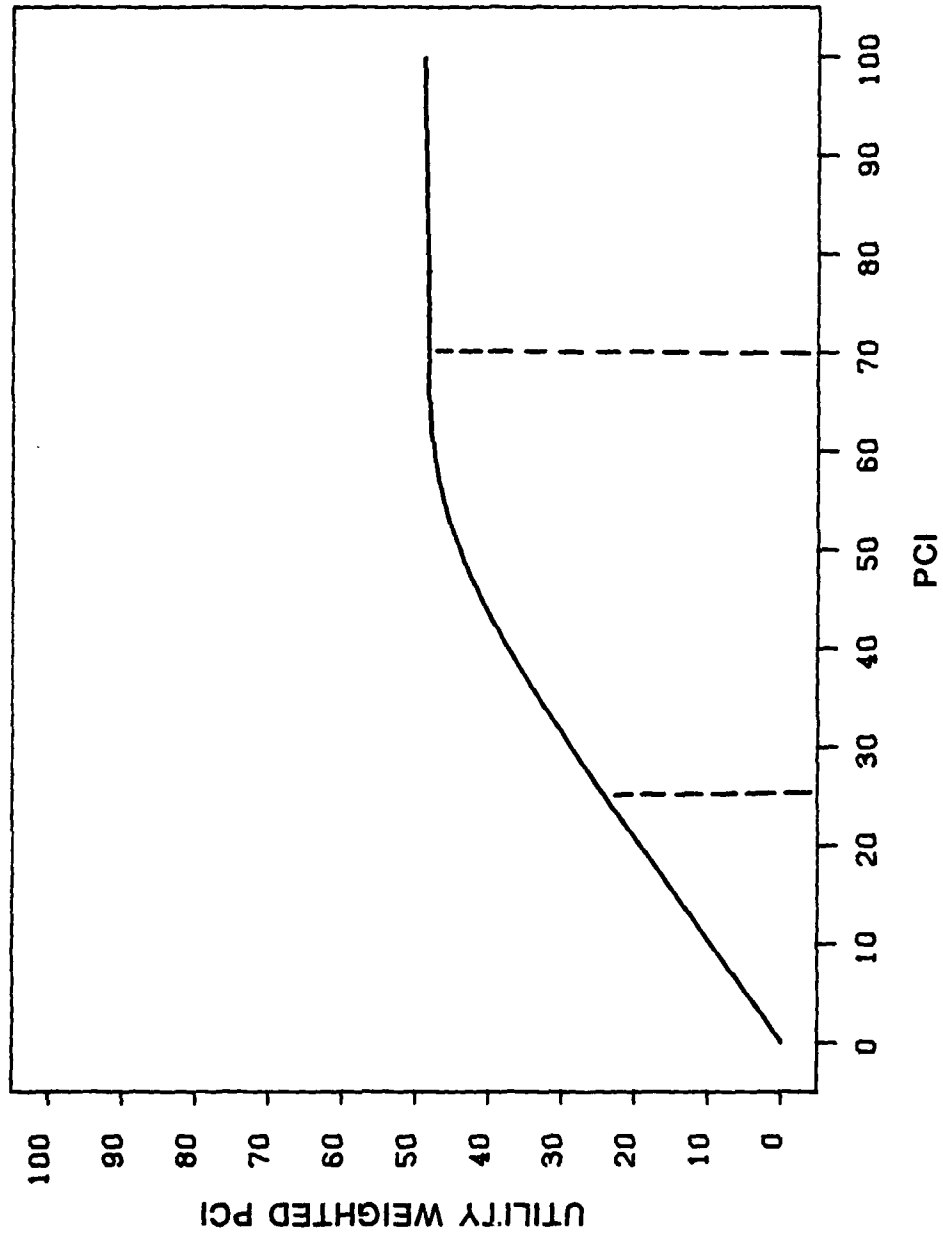


Figure 3.11 Utility Weighted PCI Versus PCI

### 3.6.3 Rehabilitative Activity Performance Measure

Using PCI and its utility, the performance of a specific rehabilitative activity can be measured over time. The performance can be measured as the area under a utility weighted PCI versus time plot (Figure 3.12). If a rehabilitative activity is applied to a pavement (as indicated by the vertical spike in the curve on Figure 3.13), the performance of the activity is measured by the area under the curve. A different activity results in a different area. The area can be calculated by integrating of the equation involving the PCI predictive equation and the PCI utility function equation, as follows.

The utility weighted PCI, as shown in Figure 3.11, can be represented by:

$$U_{PCI} = a + b*PCI + c*PCI^2 + d*PCI^3 \quad (3.5)$$

where a, b, c, and d are the regression coefficients:

$$a = -1.59$$

$$b = 1.33$$

$$c = -0.01$$

$$d = 1.17 \times 10^{-5}$$

The performance of the pavement feature as defined by the area under the utility weighted PCI versus time plot can be solved by integrating the utility of PCI with respect to age (A):

$$\text{Performance} = \int U_{PCI} dA \quad (3.6)$$

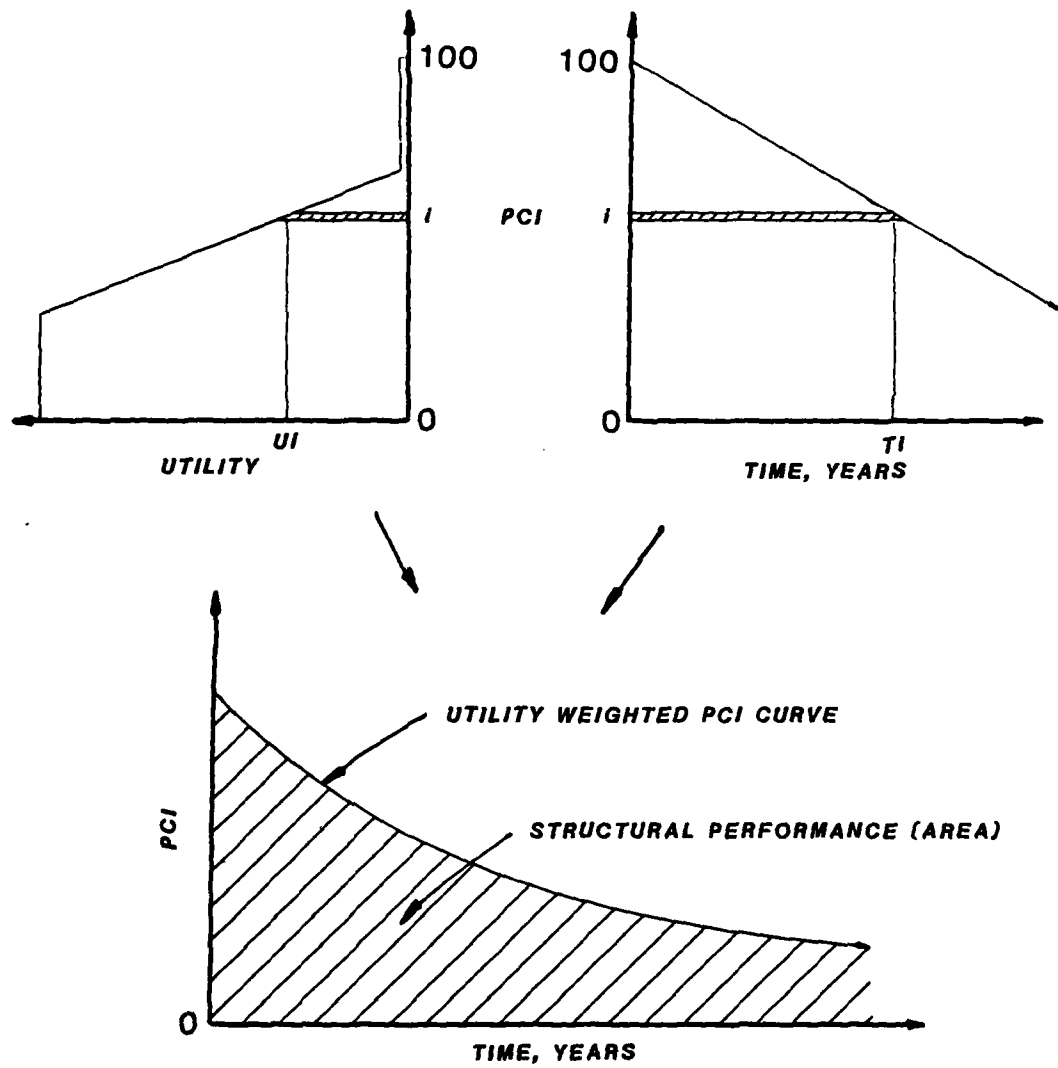


Figure 3.12 Utility Weighted PCI Versus Time Curve

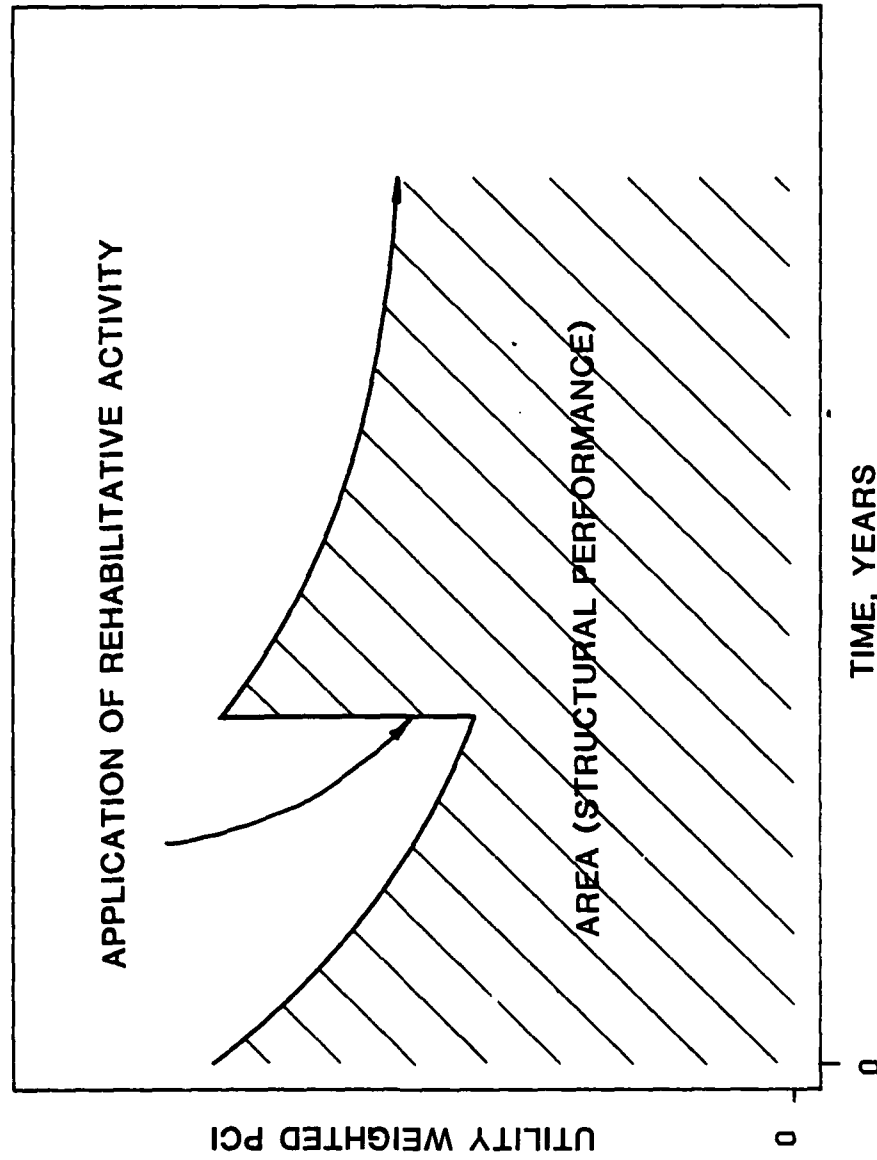


Figure 3.13 Performance of Rehabilitative Activity

where:

A = AGE = age of pavement feature in years.

By substituting Equation 3.5 into 3.6 we get:

$$\text{Performance} = \int (a + b*PCI + c*PCI^2 + d*PCI^3) dA \quad (3.7)$$

Depending on whether the feature is a Portland concrete surfaced or an asphaltic concrete surfaced pavement, the appropriate PCI predictive equation, 3.3 or 3.4, is substituted into Equation 3.7. In general Equations 3.3 and 3.4 can be represented as:

$$PCI = 100 - AGE * K \quad (3.8)$$

where:

K = parameter representing the structural, climate, and maintenance characteristics of the feature, either asphalt or concrete surfaced.

Substituting Equation 3.8 into Equation 3.7,

$$\begin{aligned} \text{Performance} = \int [a + b(100-AGE*K) + c(100-AGE*K)^2 \\ + d(100-AGE*K)^3] dA \end{aligned} \quad (3.9)$$

and evaluating Equation 3.9 evaluated from time  $T_1$  to time  $T_2$  as:

$$\begin{aligned} \text{Performance} \Big|_{T_1}^{T_2} = a*AGE - b(100-AGE*K)^2/2K - c(100-AGE*K)^3/6K \\ - d(100-AGE*K)^4/12K \Big|_{T_1}^{T_2} \end{aligned} \quad (3.10)$$

With the appropriate substitution for K, Equation 3.10 can be used to easily calculate the area under the utility weighted PCI versus time plot between time  $T_1$  and  $T_2$  in years.

### 3.7 Pavement Management Constraints

There are constraints that must be considered when developing long range rehabilitative plans. In order for the model to resemble, as closely as possible, the engineers' decision process, these constraints must be included in the dynamic programming model. The following constraints were incorporated in the model in this research:

- 1) Budget limit - total amount which the plan must not exceed (in present worth dollars).
- 2) Time in years - total time plan must not exceed (in years)
- 3) Decision intervals - scheduled points in time where activities are considered.
- 4) Minimum Distress - level of PCI which pavement must reach before any rehabilitation can be considered.
- 5) Limitation in Activity Selection - some alternatives can not be repeated (i.e., reconstruction) during the analysis period. Also overlays must be controlled by limiting the total amount of asphaltic concrete applied during the analysis period.

### 3.8 Summary

This chapter discussed the elements of an airfield, the decision process at the project level, adaptation of dynamic programming to the decision process, and the optimization criterion and constraints involved in the process. The next chapter expands on these topics as the components of the computer program developed in this research, for the project level decision process is explained.



## CHAPTER 4

## DYNAMIC PROGRAMMING MODEL FOR PROJECT LEVEL OPTIMIZATION

4.1 General

This chapter discusses the application of dynamic programming techniques to long range project level optimization. The discussion includes: explanation of the dynamic programming method and the mechanics of applying it to the project level decision process.

4.2 Dynamic Programming Method

Dynamic programming is an approach to optimization which is useful in solving specific kinds of problems. It is not a particular algorithm in that it is not a specific procedure or set of rules for finding the optimal set or solution.

"Dynamic programming is a way of looking at a problem which may contain a large number of interrelated decision variables so that the problem is regarded as if it consisted of a sequence of problems, each of which required the determination of only one (or a few) variables. Ideally, what we seek to do is, in effect, substitute solving  $n$  single variable problems for solving one  $n$  variable problem. Whenever this is possible, it usually requires very much less computational effort. Solving  $n$  smaller problems requires a computational effort which is proportional to  $n$ , the number of single variable problems if each problem contains one variable. On the other hand, solving one larger problem with  $n$  variables usually requires a computational effort which is very roughly proportional to  $a^n$ , where  $a$  is some constant. Hence the desirability of transforming or considering an  $n$ -dimensional problem as  $n$  one-dimensional problems" (29).

This method was first introduced by Bellman (41) with a stated principle of optimality. When applied to the project level decision process, Bellman's principle simplifies to:

Any optimal long range rehabilitation plan, consisting of major rehabilitative alternatives scheduled at selected points in the analysis period, is comprised of a sequence of smaller optimal sub-plans.

For example, the activities scheduled by an optimal 20 year rehabilitation plan prior to the 10 year point are still optimal if the analysis period is reduced to first 10 years.

The first advantage of dynamic programming has already been mentioned: the required search in a complex decision tree from a single  $n$ -dimensional optimization problem is reduced to  $n$  one-dimensional problems, which can be solved one at a time. A second advantage of dynamic programming is that, within the framework of the models used, global optimal solutions can be reached. Third, the embedded-solution nature of dynamic programming is useful because the same problem does not need to be repeatedly solved for various analysis period lengths. Solving the problem for the longest useful analysis period under consideration provides results for all analysis periods less than the original. Hence considerable computation time may be saved. Finally, although decision variables that are required to be integer or discrete create difficulties for other optimization techniques, their presence actually simplifies the dynamic programming solution process.

#### 4.3 Dynamic Programming Application to Project Level Decision Process

The project level decision process can be depicted as a complex decision tree with a choice of five activities (feasible decisions) at pre-established periods of time (stages). For example, Figure 4.1 illustrates the initial state of the pavement feature at time  $T_0$  and three succeeding time intervals  $T_1$ ,  $T_2$ , and  $T_3$ . Suppose that five possible activities are available at each of these time intervals. After three intervals there are  $5^3$  (125) possible combinations. If the decision tree were extended to ten intervals, a total of  $5^{10}$  (9,765,625) possible paths would exist. If a computer took 0.1 second to calculate the necessary data for analysis of each path, it would require more than 113 days to enumerate all paths. Using dynamic programming methods, the same problem, over a ten interval analysis period, could be solved in less than 25 computer seconds and still insure optimality.

Figure 4.2 is the decision tree for the same process as in Figure 4.1 except with dynamic programming methods applied. Note that the number of possible states (condition of pavement) remains the same (5) each time the five activities are applied. The five decisions (rehabilitative activities) are applied to each of the five entering states (pavement conditions). The best decision (rehabilitative activity) is selected for each of entering five conditions. These "best activity selections" reduce the number of resulting states to five. This process is repeated for each stage (analysis time period). At the

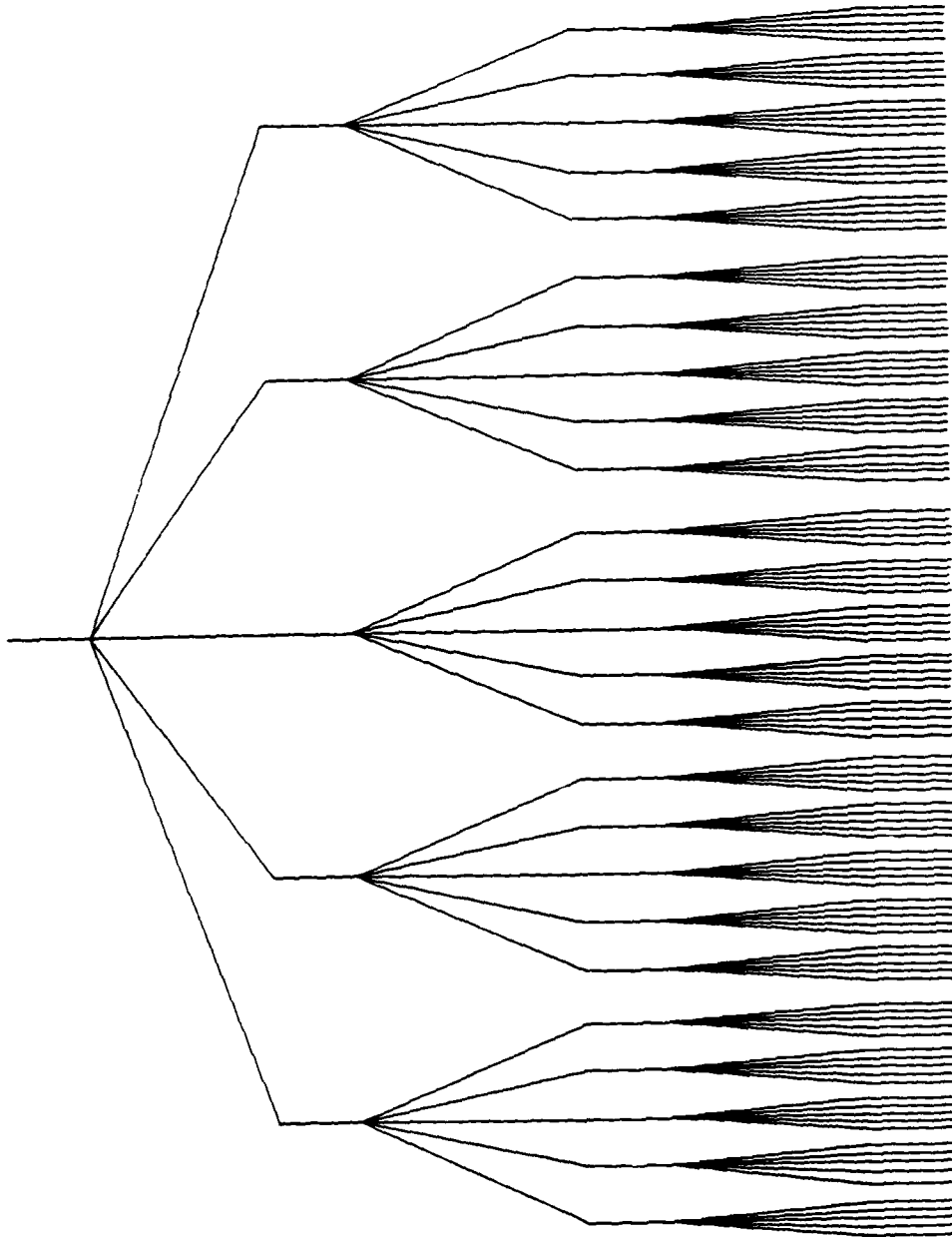


Figure 4.1 Decision Tree of Project Level Decision Process

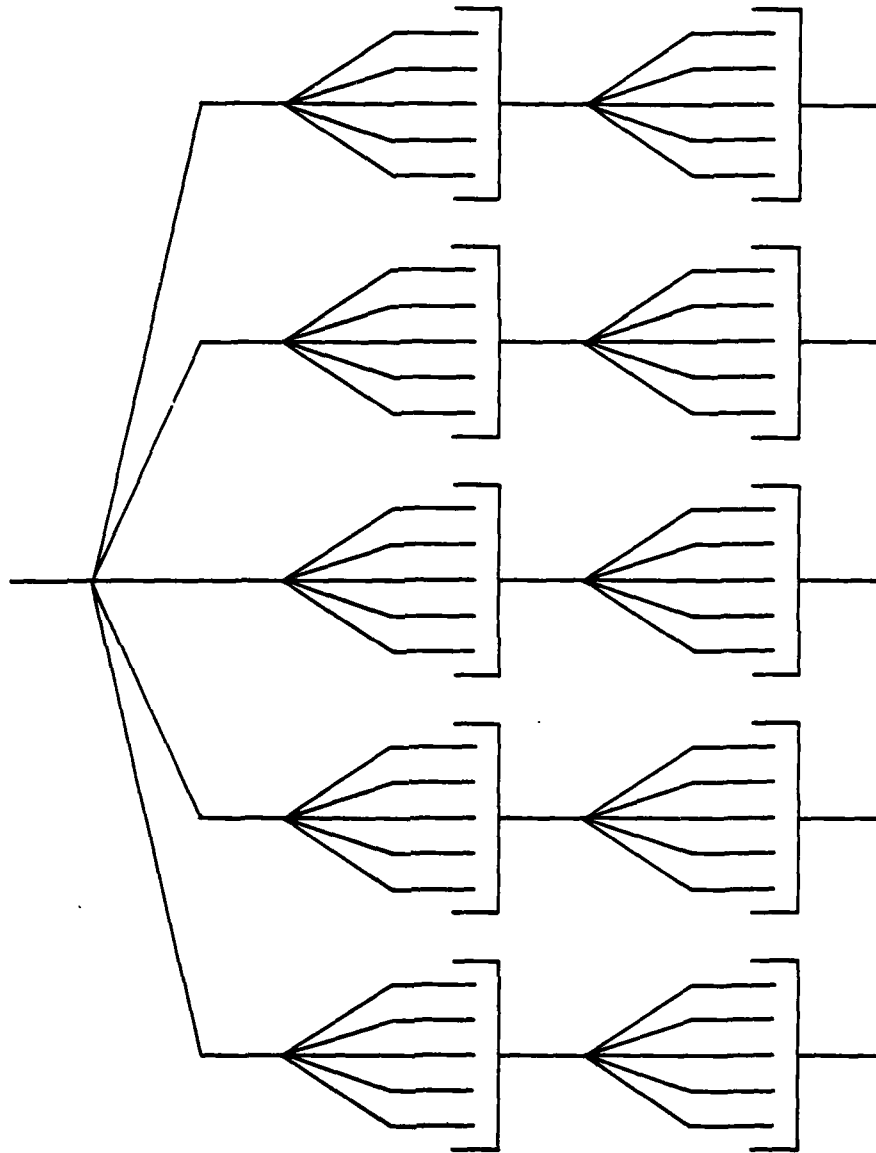


Figure 4.2 Dynamic Programming Method Applied to Project Level Decision Process

end of the analysis period with the activity selections made for each of the entering five states, another selection of these five states is made to determine the best. Selecting the best of these five terminal decision paths (states) also establishes the overall (global) best (optimal) path (set of activities). The activities selected are found by retracing the optimal path backwards through the tree.

Not only does the dynamic programming method reduce the number of paths to be analyzed, but it also reduces the amount of computer memory necessary to store the number of paths which must be saved for possible retracing.

Summarizing, a decision path is set of rehabilitative activities scheduled at specific time intervals during the analysis period. Dynamic programming methods reduce the total number of decision paths to be analyzed, searching for the optimal or best path. Traditional decision tree analysis is multiplicative in nature as the number of stages (analysis periods) increases. Whereas, with dynamic programming methods, the decision process is only additive in nature.

#### 4.3.1 Dynamic Programming Model Flow Chart

The dynamic programming method, as applied to the project level decision process, is illustrated in Figure 4.3. Each stage represents a pre-established schedule point during the analysis period. The five

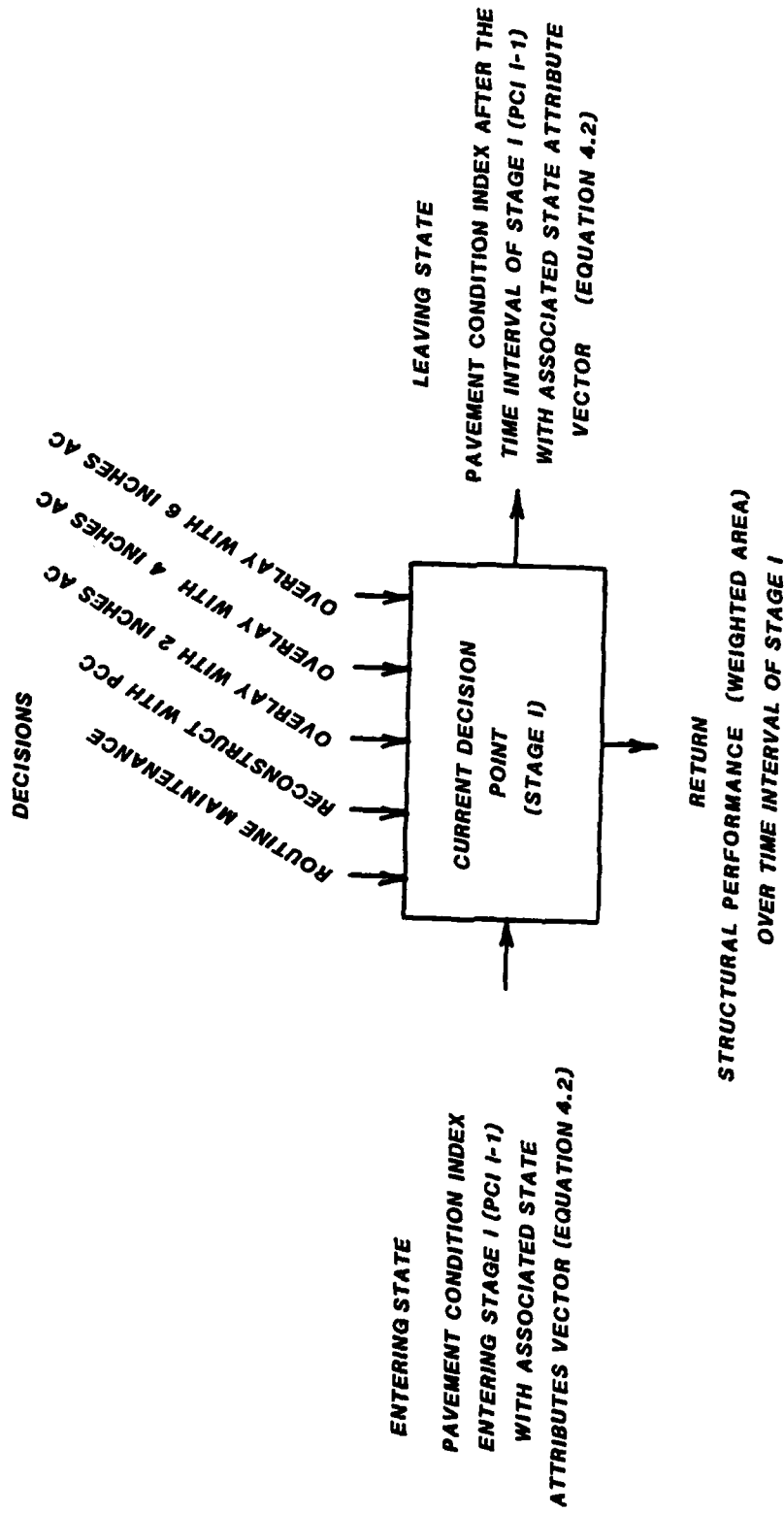


Figure 4.3 Dynamic Programming Model Flow Chart



decisions (activities) applied at each state are:

- 1) Routine Maintenance (R/M)
- 2) Reconstruction with PCC (R/C)
- 3) Overlay with 2 inches of AC (O/L2)
- 4) Overlay with 4 inches of AC (O/L4)
- 5) Overlay with 6 inches of AC (O/L6)

Substitution or addition of other activities could be done. These decisions are represented as the vector  $[D]$  and defined as follows:

$$[D] = [d_1, d_2, d_3, d_4, d_5] \quad (4.1)$$

The single independent state variable, PCI, is required for this dynamic programming formulation. When entering into any stage  $i$ , it can have only one of five values. Associated with the PCI are 14 other dependent state variables.

Each of the five possible entering states is defined by a single row vector of independent and dependent state variables values as:

$$[s_{ij}] = [a_{i1}, a_{i2}, a_{i3}, \dots, a_{ij}, \dots] \quad (4.2)$$

with  $a_{ij}$  as one of the following attributes:

- 1) Pavement Condition Index (PCI)
- 2) Performance or area under curve (BENEFIT)

- 3) Expended cost (COST)
- 4) Age of the pavement (AGE)
- 5) Alpha under the asphalt layer ( $\alpha_{ac}$ )
- 6) Alpha on the subgrade ( $\alpha_{sg}$ )
- 7) Age of the overlay (AGECOL)
- 8) Thickness of the asphalt layer ( $T_{ac}$ )
- 9) Thickness of the PCC layer ( $T_{pcc}$ )
- 10) Percent slabs replaced (SR)
- 11) Whether or not the pavement has been overlaid (ACOL)
- 12) Percent of area patched (PATCH)
- 13) Age since original construction (IAGE)
- 14) Whether flexible or rigid pavement (PVTYP)
- 15) Selected rehabilitative activity (DECIDX)

where:

$i$  = index of the possible enter states

$j$  = index of the attributes

The entire entering set of states for the pavement can be represented in a single array,  $[S]_n$  for each stage  $n$  and defined as:

$$[S]_n = \begin{bmatrix} a_{11}, a_{12}, a_{13}, \dots, a_{1j} \\ a_{21}, a_{22}, a_{23}, \dots, a_{2j} \\ a_{31}, a_{32}, a_{33}, \dots, a_{3j} \\ \vdots \\ a_{ij}, a_{i2}, a_{i3}, \dots, a_{ij} \end{bmatrix}_n \quad (4.3)$$

where:  $n$  = index of stages

The return value (optimization criteria) is used to select the best activity. The return function in this model is the total area under the utility weighted PCI versus time curve. The values of the return function are represented by  $[R]$  and defined as:

$$[R] = [r_1, r_2, r_3, r_4, r_5] \quad (4.4)$$

where  $r_m$  represent the return of the selected activity for each state when all the activities are applied to each entering state. The optimal (best) returns are then kept and carried forward to the next state as members of the state variable array,  $[S]_n$ . They are stored as the performance attribute, BENEFIT.

The dynamic programming model can be represented mathematically as follows:

Maximize:

$$\sum_{L=1}^n \int_{T_1}^{T_2} [-1.59 + 1.33*PCI_i - 0.01*PCI_i^2 + 1.17*10^{-5}*PCI_i^3] dt \quad (4.5)$$

with the following constraints or attribute transformations:

PCI limits for all stages  $i$

$$0 \leq \text{PCI}_i \leq 100 \text{ for all } i \quad (4.6)$$

Determination of PCI for all stages i

$$\text{PCI}_i = 100 - \text{AGE}_{100} * K \quad (4.7)$$

Decision (activity) feasibility for all stages i

If  $0 \leq \text{PCI}_{i-1} \leq 70$  then the feasible decisions are:

$d_1, d_2, d_3, d_4, d_5$

Else if  $70 < \text{PCI}_{i-1} \leq 100$  then the only feasible decision is:

$d_1$ , routine maintenance only (4.8)

Project cost limitation for all stages i

$$\text{COST}_i \leq \text{Project Funding Limit (MAXCOST)} \quad (4.9)$$

Age of the pavement for all stages i

$$\text{AGE}_i = \text{AGE}_{i-1} + \text{stage } i \text{ interval length} \quad (4.10)$$

Thickness of asphalt layer for all stages i

If the decision at the beginning of stage i was:

$d_1$  then  $\text{Tac}_i = \text{Tac}_{i-1}$

$d_2$  then  $\text{Tac}_i = 0$

$$\begin{aligned}
 d_3 \text{ then } Tac_i &= Tac_{i-1} + 2 \\
 d_4 \text{ then } Tac_i &= Tac_{i-1} + 4 \\
 d_5 \text{ then } Tac_i &= Tac_{i-1} + 6
 \end{aligned}
 \tag{4.11}$$

Thickness of Portland cement concrete slab for all stages i

If decision at the beginning of stage i was:

$$\begin{aligned}
 d_1, d_3, d_4, d_5 \text{ then } Tpcc_i &= Tpcc_{i-1} \\
 d_2 \text{ then } Tpcc_i &= \text{reconstructed pcc thickness}
 \end{aligned}
 \tag{4.12}$$

Structural parameters of flexible pavement for all stages i

$$\begin{aligned}
 \alpha_i &= (T_i/A^{0.5}) * [0.048 - 1.1562 \log(CBR/pe) \\
 &\quad - 0.06414 \log(CBR/pe)^2 - 0.473 \log(CBR/pe)^3]
 \end{aligned}
 \tag{4.13}$$

where:

$T_i$  = thickness of layer above point of interest in pavement  
(just under AC and on top of the subgrade)

A = contact area of one tire of aircraft (psi)

CBR = California Bearing Ratio of underlying layer

pe = tire pressure (psi) calculated using contact

area A, and the equivalent single-wheel load (ESWL)

determined at depth  $T_i$

Age or overlay for all stages i

If the decision at the beginning of stage i was:

$$d_1 \text{ then } AGECOL_i = AGECOL_{i-1}$$

$$\begin{aligned}
 & d_2 \text{ then } AGE_{COL_i} = 0 \\
 & d_3, d_4, d_5 \text{ then } AGE_{COL_i} = IAGE_i
 \end{aligned} \tag{4.14}$$

Percent of slabs replaced for all stages i

$$SR_i = 88.622 - 1.993 * PCI_i + 0.012 * PCI_i^2 - 1.127 * PCI_i^3 \tag{4.15}$$

Pavement overlay status for all stages i

If the decision at the beginning of stage i was:

$$\begin{aligned}
 & d_1 \text{ then } ACOL_i = ACOL_{i-1} \\
 & d_2 \text{ then } ACOL_i = 0 \\
 & d_3, d_4, d_5 \text{ then } ACOL_i = 1
 \end{aligned} \tag{4.16}$$

Percent of feature patched for all stages i

$$PATCH_i = 32.204 + 0.1306 * PCI_i - 0.0098 * PCI_i^2 + 5.28 * 10^{-5} * PCI_i^3 \tag{4.17}$$

Age since original construction or reconstruction for all stages i

If decision at the beginning of stage i was:

$$\begin{aligned}
 & d_1, d_3, d_4, d_5 \text{ then } IAGE_i = IAGE_{i-1} + \text{stage interval length} \\
 & d_2 \text{ then } IAGE_i = 0
 \end{aligned} \tag{4.18}$$

Pavement type index (rigid = 1 and flexible = 2 ) for all stages i

If the decision at the beginning of stage i was:

$$\begin{aligned}
 d_1, d_3, d_4, d_5 \text{ then } PVTYP_i &= PVTYP_{i-1} \\
 d_2 \text{ then } PVTYP_i &= 1
 \end{aligned}
 \tag{4.19}$$

Selected rehabilitation activity for all stages i

If the decision at the beginning of stage i was:

$$\begin{aligned}
 d_1 \text{ then } DECIDX_i &= 1 \\
 d_2 \text{ then } DECIDX_i &= 2 \\
 d_3 \text{ then } DECIDX_i &= 3 \\
 d_4 \text{ then } DECIDX_i &= 4 \\
 d_5 \text{ then } DECIDX_i &= 5
 \end{aligned}
 \tag{4.20}$$

where:

$d_1, d_2, \dots, d_5$  = decision of routine maintenance; reconstruction with pcc; and overlays of 2, 4, and 6 inches of AC respectively

$i$  = stage index

$n$  = number of stages in analysis period

$AGE_{100}$  = time since pavement was at PCI = 100

If the feature was rigid then:

$$\begin{aligned}
 K &= 0.01967 * FAT - 0.02408 * SR + 0.001051 * (JSL * JSS) + 2.10579 * ACOLTHK^{-0.81} \\
 &\quad + 0.03475 * PATCH + 2.91238 - 0.001775 * FI - 0.04066 * TEMP
 \end{aligned}
 \tag{4.21}$$

Else if the feature was flexible then:

$$K = 1.487 / \alpha_{sg} + 0.143 * AGECOL + 6.56 / T_{ac} - 1.73 * \alpha_{ac} \quad (4.22)$$

Note that the variables needed to determine K are explained in Chapter 3.

The single independent state variable in this dynamic programming algorithm is PCI. Associated with this state variable is a vector of state variable attributes dependent on the PCI state variable and the feasible decisions. Because of the nature of the decisions available, at any stage (decision point) during the analysis period there can be no more than five values of the state variable.

#### 4.3.2 Computer Program Description

A computer program was written for using dynamic programming methods for selecting and scheduling the set of rehabilitative activities that optimize (maximize) the objective function (performance as defined as the utility weighted PCI versus time curve).

The program was written in Control Data Corporation's Fortran V (which generally adheres to the Fortran 77 ANSI standards). It is a 2900 line program with 73 subroutines supporting the main program. Figure 4.4 is a flow chart showing the major elements of the dynamic programming algorithm as applied to the project level decision process.



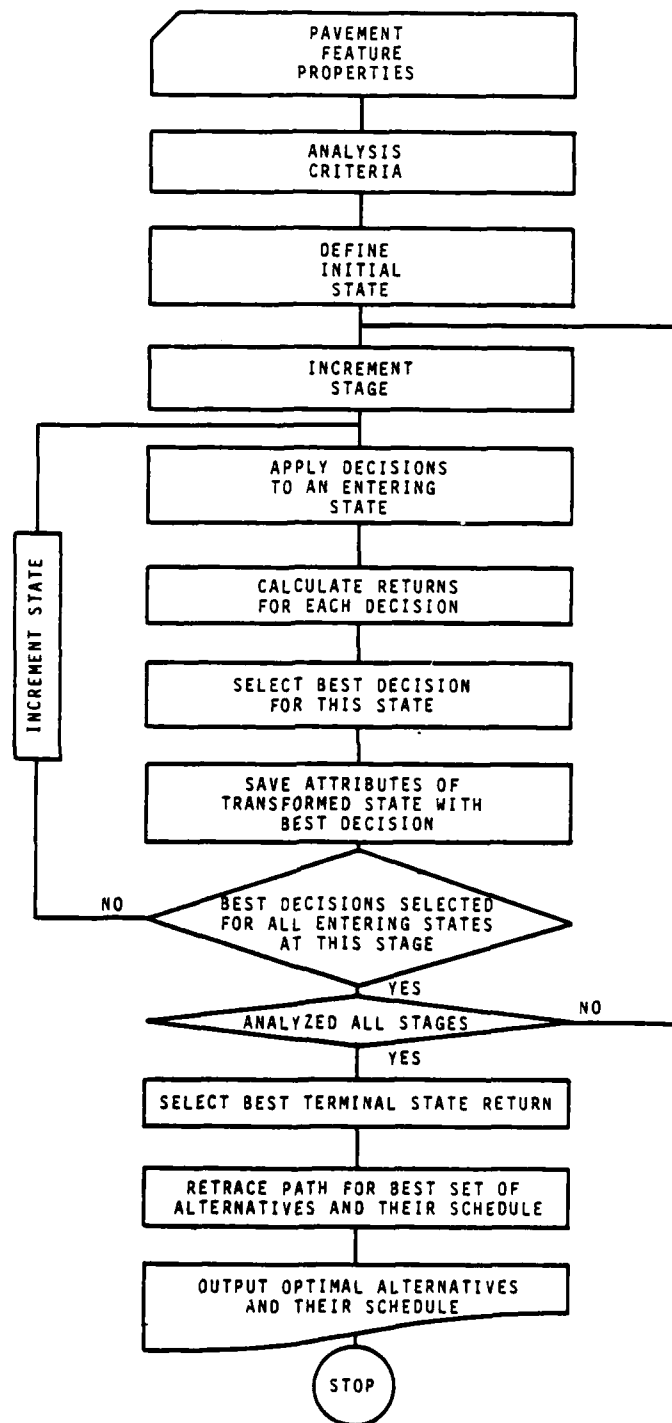


Figure 4.4 Project Level Computer Program Flow Chart with Dynamic Programming Methods

After the feature data and the analysis criteria are entered via condensed data sets, the problem is initialized. As shown in the flow chart, Figure 4.4, the decision process is repetitive, applying the five decisions to each of the five states at each stage, and generating the five new states for the next stage. The process is continued until all the stages in the analysis period are completed.

#### 4.3.3 Computer Program Inputs

Input data for the computer program are read from two condensed data files: analysis criteria data and feature property data.

##### 4.3.3.1 Analysis Criteria Data

The data necessary for characterizing the dynamic programming analysis are input from a separate data file. The information are read in condensed form as follows:

- 1) Number of stages or intervals in the analysis period  
(NUMSTG)
- 2) Ages of each interval in analysis period, stage ages (STGAGE) and terminal age of analysis period, final stage age (FSTGAGE).
- 3) Condition rating of pavement (PCI) above which no rehabilitative activities will be accomplished (PCIMIN)

- 4) Interest and inflation rates for use during the analysis period (INTRST and INFLTN)
- 5) Control variables to restrict the type and amount of output.

#### 4.3.3.2 Pavement Feature Data Input

A condensed data set is read into the program from a separate data file containing features in the network. After finishing the analysis on one pavement feature, the program reinitializes the entire process and reads in data for another feature and continues until all have been analyzed. The data read into the program for each feature are:

- 1) Base or airfield name (BNAME)
- 2) Pavement feature name (FNAME)
- 3) Pavement type, rigid or flexible (PTYPE)
- 4) Feature length, width and current age (LNGTH, WIDTH and IAGE)
- 5) If the feature is flexible then, number of layers in pavement, overlay thickness, age of the overlay, and the physical properties of each layer, thickness, type and CBR (NUMBRLYR, OATHK, AGEVOL, LYRTYP, LYRTHK, and LYRCBR). Additionally, the current PCI, average annual temperature, and freezing index are listed (OIPCI, TEMP, and FI).
- 6) If the feature is rigid, the pavement characteristics are input, slab size, modulus of rupture, modulus of soil reaction,

slab thickness, overlay thickness, current PCI, percent slabs replaced, freezing index, percent of feature area patched, average annual temprature, and the age of the last overlay (JSL, JSS, MDRPTR, KMPD, OPTHK, OATHK, OIPCI, SR, FI, PATCH, TEMP, AGECOL).

- 7) Design aircraft data, identification and weight (ARCFTID and ARCFTWT).
- 8) Using aircraft type, mission, and number (ARCFTCD, ARCFTMS, and ARCFTN).
- 9) Pavement feature use and need (PVTUSE and PVTND).
- 10) Feasible rehabilitative activity data, maximum asphaltic concrete overlay thickness, reconstruction portland cement concrete thickness, overlay cost, reconstruction cost, reconstructed modulus of rupture, reconstructed modulus of soil reaction, reconstructed slab size (MXACTHK, RPCTHK, OLCST, RCSTCST, RMDRPTR, RKMOT, RJSL, RJSS)

#### 4.3.4 Computer Program Algorithms

In addition to the algorithms used to describe the PCI, PCI utility, and the area under the utility weighted PCI versus time curve, functions were developed to determine:

- 1) Total Feature Worth (TFW) to user
- 2) Percent of feature area patched

- 3) Percent of feature with shattered slabs
- 4) Equivalent single wheel loads
- 5) Interior stress at the bottom of the slab
- 6) Cost of preparing pavement for overlays

#### 4.3.4.1 Total Feature Worth to User

Total feature worth to the user establishes the relative value of the pavement feature to the user with respect to the entire network. It is not part of the dynamic programming analysis but it is a function of the data used as input into the dynamic programming analysis. The TFW is included in the output of the dynamic programming analysis for use in the network analysis. Although the function TFW is used in following chapters, an explanation is included here because it is output from the dynamic programming computer program.

The TFW represents relative value to the using aircraft of a feature as compared to another feature, whether on the same base or another base. It is a function of the following variables:

- 1) Pavement type (runway, taxiway, etc.)
- 2) Pavement need (primary, secondary, etc.)
- 3) Using aircraft type (bomber, fighter, cargo, etc.)
- 4) Using aircraft mission (alert, training, operational, etc.)

5) Number of using aircraft by type and mission.

Together these variables describe the relative worth of one particular pavement feature versus another. Table 4.1 shows the complete breakdown of each category in addition to the numerical value assigned to each variable element. These assignments have been estimated by the author based on 6 years of experience in Air Force pavement management, but should be validated prior to implementation.

The TFW of a single feature is determined by the following relation:

$$TFW = \sum_{L=1}^n N_i * (PT_i + PN_i + AT_i + AM_i) \quad (4.23)$$

where:

- $N_i$  = number of using aircraft by type and mission
- $PT_i$  = pavement type coefficient for using aircraft
- $PN_i$  = pavement need coefficient for using aircraft
- $AT_i$  = using aircraft type coefficient
- $AM_i$  = using aircraft mission coefficient
- $i$  = counter of different using aircraft types
- $n$  = number of different aircraft types using feature

The information necessary for the worth calculation is readily available at each Air Force base.

Table 4.1 Element Weights of Total Feature Worth Calculation

Characteristic (#)	Criteria (##)	Relative Weight (###)
Aircraft Mission (10)	Alert (100)	1000
	Operational (50)	500
	Training (10)	100
Pavement Need (5)	Primary (100)	500
	Secondary (20)	100
	Auxiliary (5)	25
	Transient (2)	10
	None (1)	5
Pavement Type (2.5)	Runway (100)	250
	Taxiway (30)	75
	Apron (10)	25
Aircraft Type (0.5)	Bomber (100)	50
	Command (50)	25
	Tanker (30)	15
	Cargo (20)	10
	Fighter (10)	5
	Transport (8)	4
	Reconnaissance (6)	3
	Trainer (4)	2
	Experimental (2)	1

# Relative weight of Characteristics as a group.  
 ## Relative weights of Criteria with in the Characteristics.  
 ### Product of Characteristic and Criteria weight.

#### 4.3.4.2 Percent of Feature Area Patched

Because the percent of the feature patched is used in the PCI predictive equation for rigid pavements, it was necessary to forecast its value. Since it is not a primary focus of this research to develop a comprehensive set of regression equations for predicting the percent area of feature patch as a function of PCI, only a simple analysis using 91 data points from a single airfield was used in this research. These points were used to determine the coefficients of a third order polynomial:

$$\text{PATCH} = a + b*\text{PCI} + c*\text{PCI}^2 + d*\text{PCI}^3 \quad (4.24)$$

where:

PATCH = percent of slabs patched (patch larger than 5 ft<sup>2</sup>)

PCI = pavement condition index

with the coefficients:

$$a = 32.204$$

$$b = 0.1306$$

$$c = -0.0098$$

$$d = 5.28*10^{-5}$$

Figure 4.5 depicts a graph of this equation.



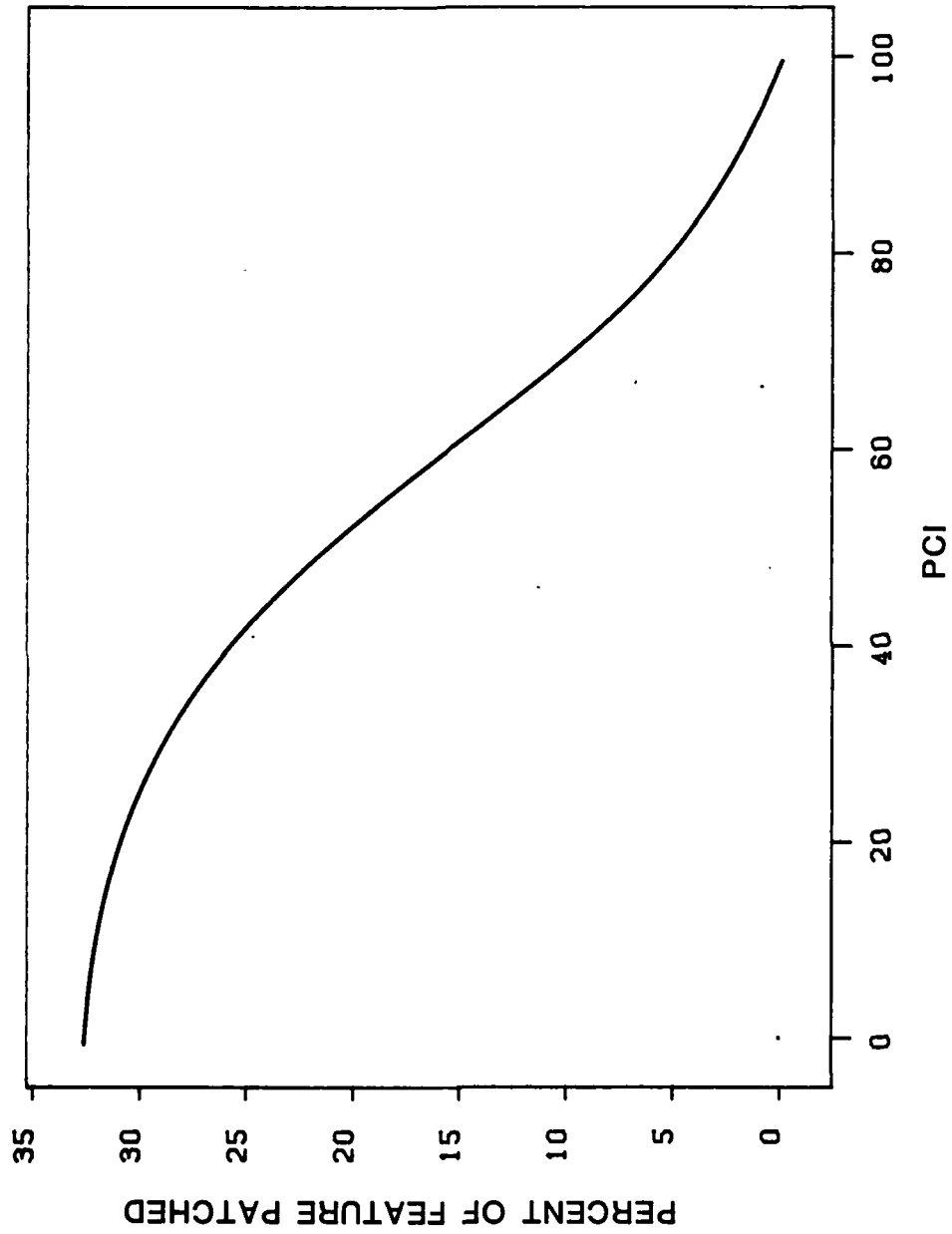


Figure 4.5 Percent of Feature Patched Versus PCI

#### 4.3.4.3 Percent of Feature with Shattered Slabs

The percent slabs replaced (SR) in a feature is also part of the PCI predictive equation. For use in the dynamic programming algorithm, a simple third order equation was fit from data extrapolated from the PCI manual (27) as follows:

$$SR = a + b*PCI + c*PCI^2 + d*PCI^3 \quad (4.25)$$

where:

$$\begin{aligned} a &= 88.622 \\ b &= -1.993 \\ c &= 0.012 \\ d &= -1.127*10^{-5} \end{aligned}$$

This equation predicted the number of high severity shattered slabs and was used as the basis for determining the percent slabs replaced in the feature.

#### 4.3.4.4 Equivalent Single Wheel Load (ESWL)

The terms  $s_g$  and  $a_c$  in Equation 3.4 require the equivalent single wheel load (ESWL) of the using aircraft. In current practice the procedures for determining ESWL use charts and tables(8). In order to simplify the computer program and to save significant computation time,

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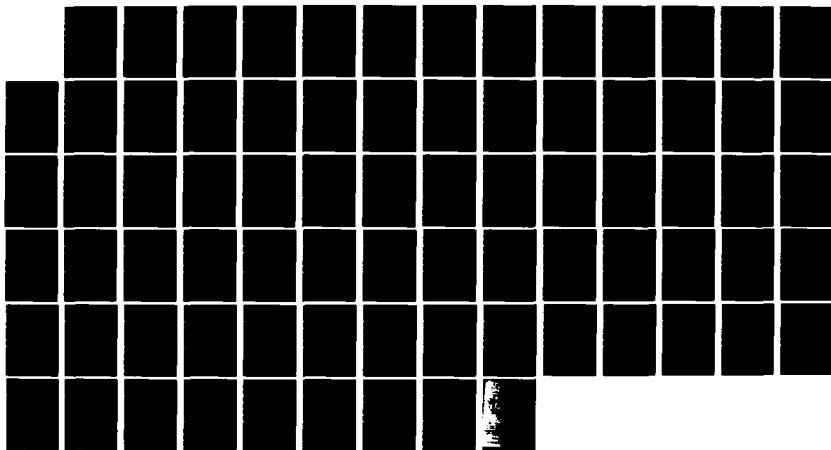
OPTIMIZATION OF LONG RANGE MAJOR REHABILITATION OF  
AIRFIELD PAVEMENTS(U) AIR FORCE INST OF TECH  
WRIGHT-PATTERSON AFB OH D H ARTHAN JAN 83  
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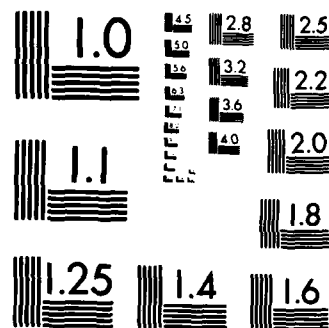
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MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

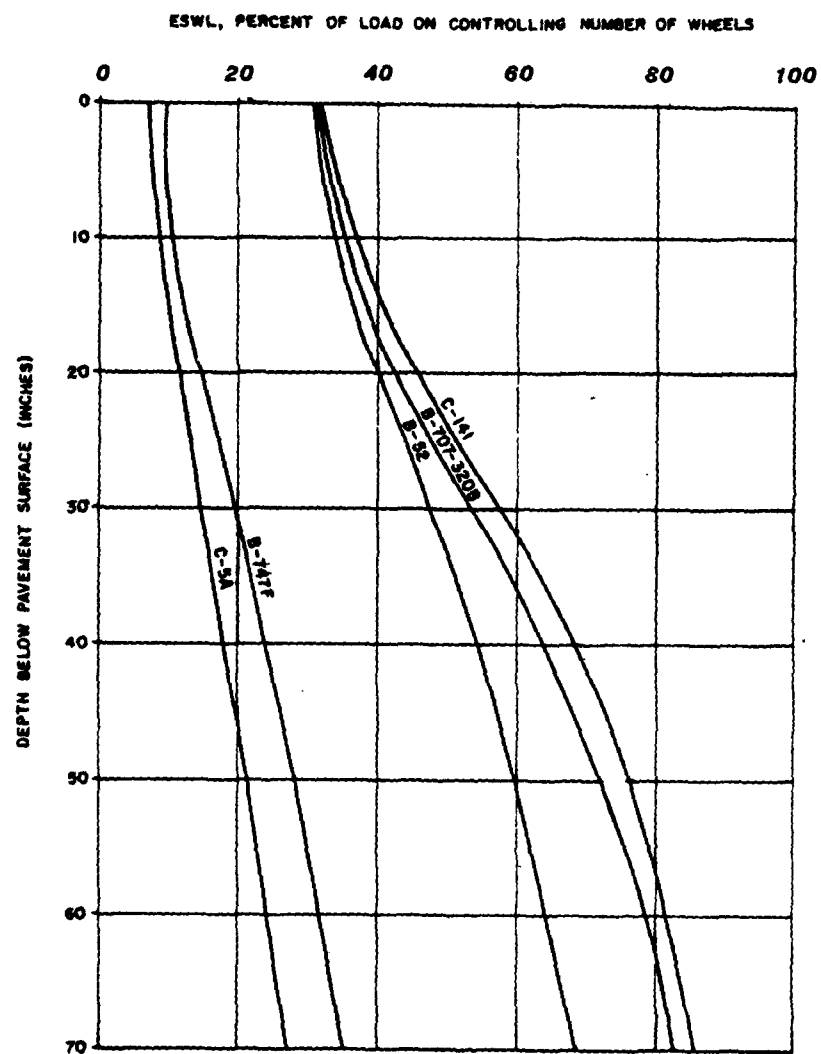


Figure 4.6 ESWL as Function of Aircraft Type and Depth Below Pavement Surface (31)

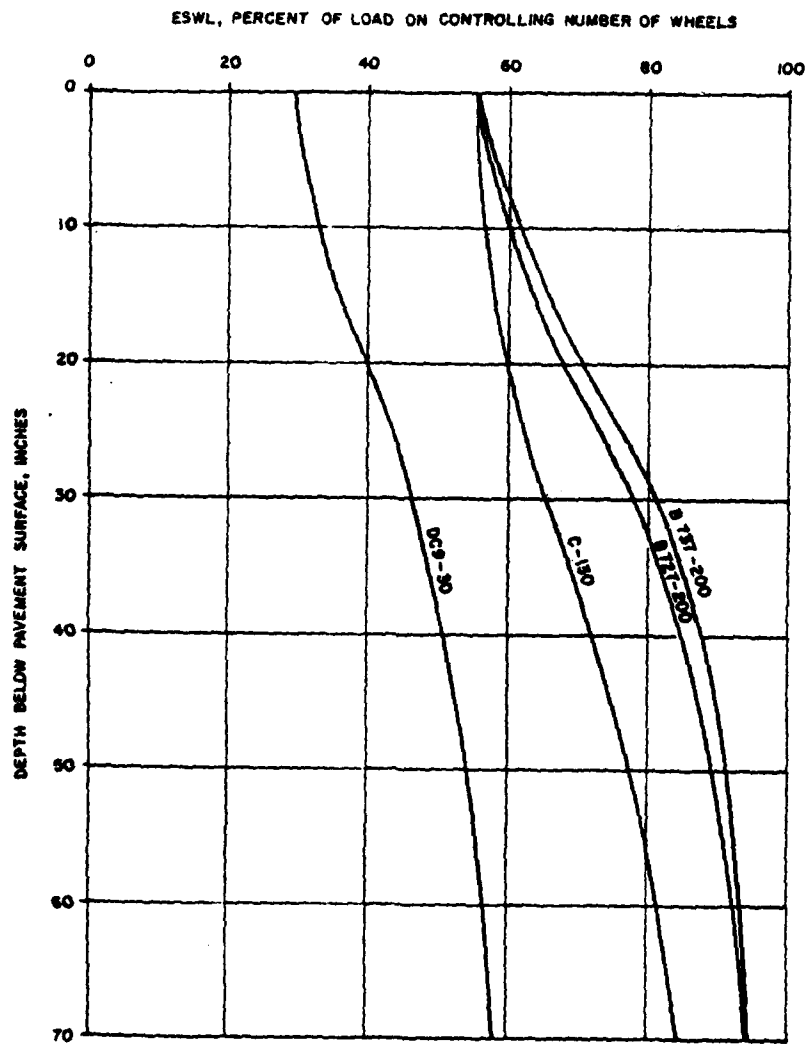


Figure 4.7 ESWL as Function of Aircraft Type and Depth Below Pavement Surface (31)

a third order polynomial was fit to Figures 4.6 and 4.7. The equation is:

$$ESWL = C_{m1} + C_{m2}*D + C_{m3}*D^2 + C_{m4}*D^3 \quad (4.26)$$

where:

ESWL = equivalent single wheel load as a percent of total controlling wheel load (8).

D = depth to point of interest in pavement system in inches.

$C_{mn}$  = coefficients of polynomial from Table 4.2

m = using aircraft index

n = coefficient index

#### 4.3.4.5 Interior Stress at Bottom of Slab

The term FAT in the PCI predictive Equation 3.3, is a function of the induced and allowable stresses in the slab. It also is current practice to use charts and graphs for determining the interior stress at the bottom of the slab (8). For ease in computation, instead of using Figures 4.8, 4.9 and 4.10 for interior stress determination, regression equations were developed.

The following equation form was used with the coefficients regressed for the three cases, single, dual, and tandem wheel configurations:

Table 4.2 Coefficients for Equation 4.25 (Cmn), Equivalent Single Wheel Load

$\begin{matrix} m \backslash n \\ 1 \end{matrix}$	1	2	3	4	USING AIRCRAFT
1	29.4394	0.4746	0.0064	$-9.34 \times 10^{-5}$	C-9
2	9.6061	0.1456	0.0078	$-6.57 \times 10^{-5}$	E-4
3	30.5303	0.3321	0.0104	$-1.06 \times 10^{-4}$	B-52
4	31.7879	0.2269	0.02324	$-2.30 \times 10^{-4}$	KC-135
5	31.6515	0.11865	0.03271	$-3.36 \times 10^{-4}$	C-141
6	55.106	0.00273	0.01649	$-1.49 \times 10^{-4}$	C-130
7	7.0152	0.1238	0.0060	$-5.3 \times 10^{-4}$	C-5
8	54.3789	0.83968	0.00343	-0.0001	T-43

m - using aircraft index

n - coefficient index



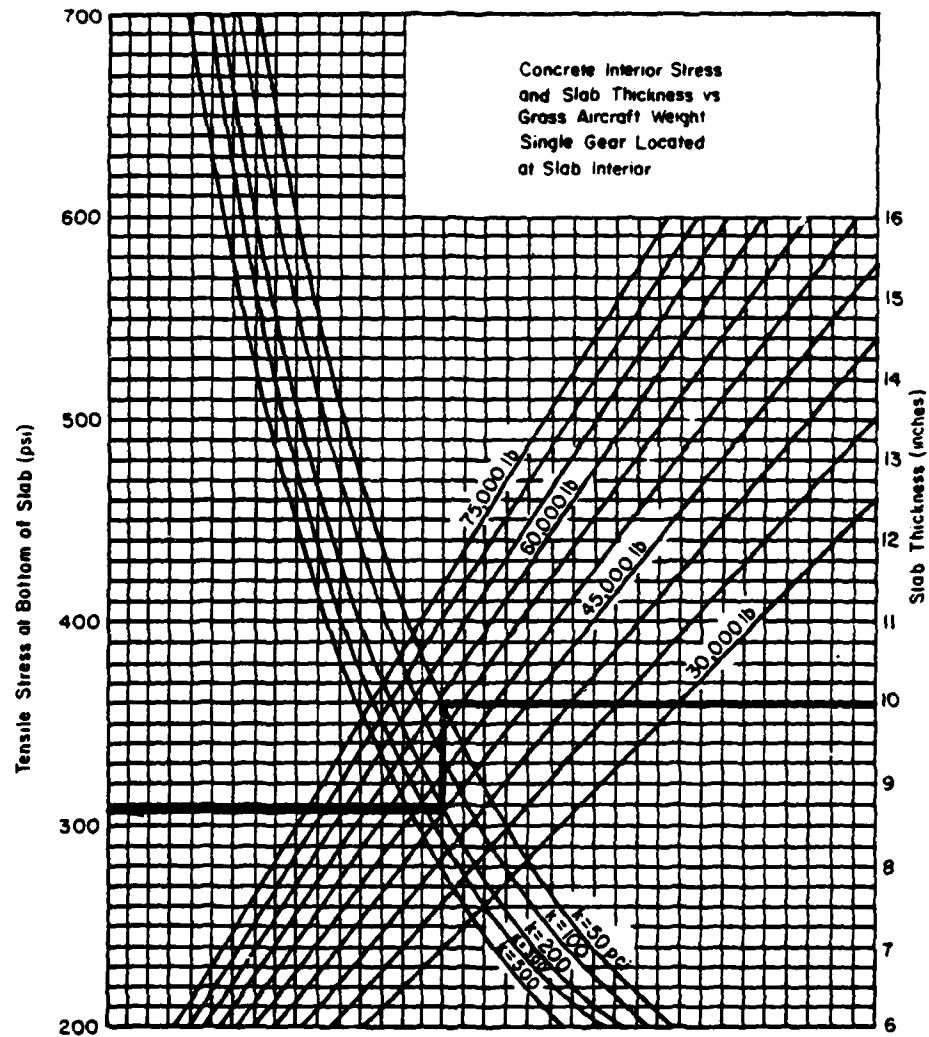


Figure 4.8 Interior Stress at the Bottom of the Slab from Single Wheel Loading (8)

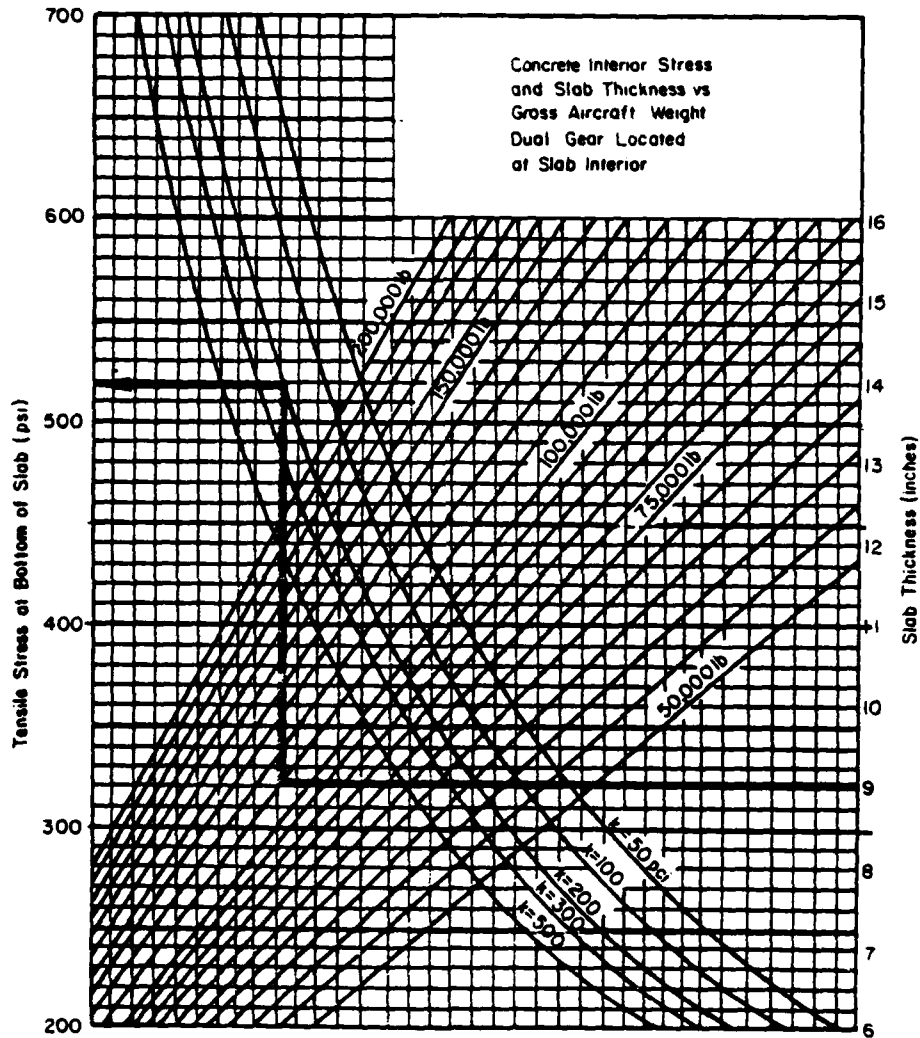


Figure 4.9 Interior Stress at the Bottom of the Slab from Dual Wheel Loading (8)

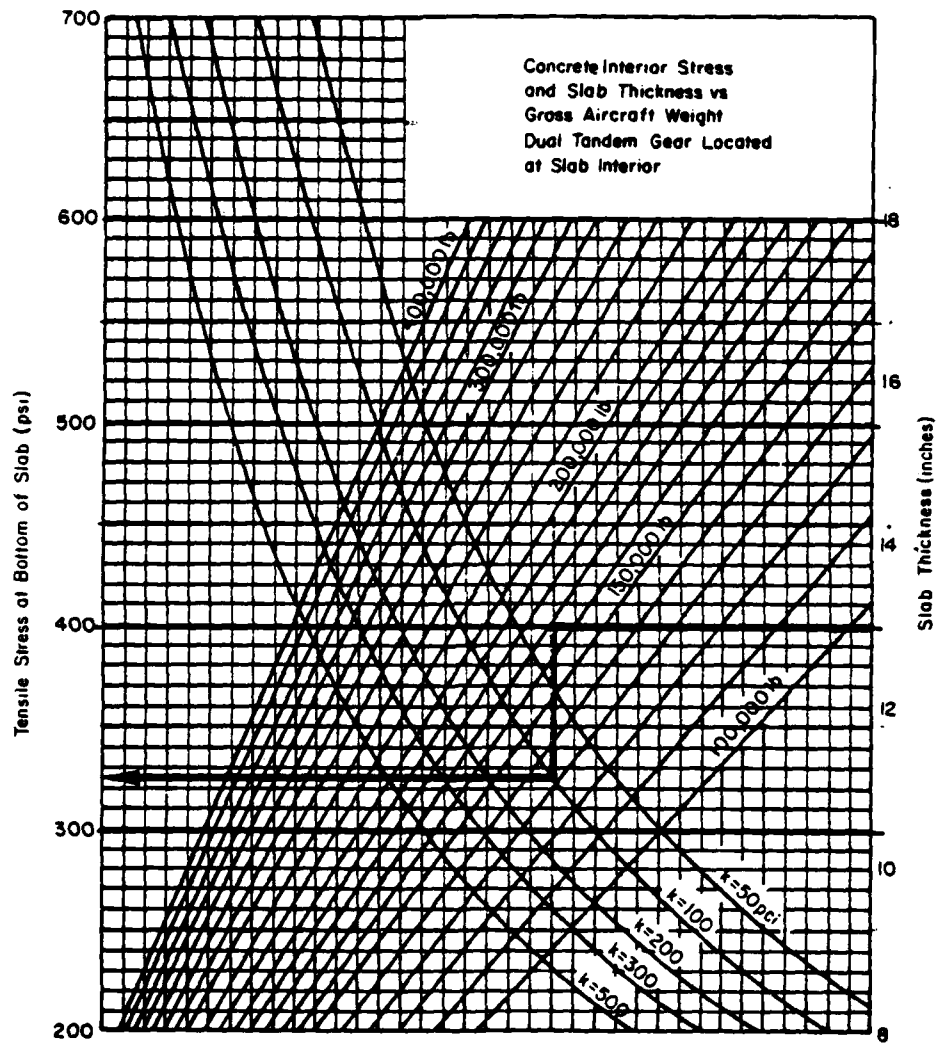


Figure 4.10 Interior Stress at the Bottom of the Slab from Tandem Wheel Loading (8)

$$\begin{aligned}
 \text{SLBSTRS} = & C_{m1} * F1 + C_{m2} * F2 + C_{m3} * IT2 + C_{m4} * LGK \\
 & + C_{m5} * LGT + C_{m6} * LGL + C_{m7} * IL + C_{m8}
 \end{aligned}
 \tag{4.27}$$

with:

$$F1 = L/T^2 * \log_{10}(24.165 * T^{0.75} / K^{0.25})$$

$$F2 = L/T^2$$

$$IT2 = 1/T^2$$

$$LGK = \log_{10}(K)$$

$$LGT = \log_{10}(T)$$

$$LGL = \log_{10}(L)$$

$$IL = 1/L$$

$C_{mn}$  = regression coefficients from Table 4.3

$n$  = coefficient index, 1 thru 8

$m$  = aircraft wheel type, 1, 2, or 3

where:

$L$  = aircraft load in pounds

$K$  = modulus of soil reaction in pounds per square inch per inch

$T$  = slab thickness in inches

#### 4.3.4.6 Cost of Preparing Pavement for Overlay

The cost of overlaying a pavement in the future must reflect the condition of the pavement feature at the time of the overlay. The worse condition a pavement is in (lower PCI) the more it costs to repair the pavement in preparation for the overlay. A data set of 200 features

Table 4.3 Coefficients for Equation 4.26 (Cmn), Interior Stress  
at the Bottom of the Slab

$\frac{n}{m}$	1	2	3	4	5	6	7	8
1	0.63525	-0.55573	3394.572	-12.4126	-140.0759	47.4639	-666785	-78.81812
2	0.53716	-0.48946	3877.272	-17.5810	-58.8898	-281.3764	-11409428	1644.823
3	0.46293	-0.55527	1088.031	-24.3478	-51.9977	-413.842	-37573891	2518.7271

single wheel - m=1  
dual wheel - m=2  
tandem wheel - m=3

were analyzed from airfields around the country, to determine the cost of preparing the pavement feature for overlay. The following equation resulted from regression of the data:

$$\text{PREPCST} = 264.70 * \text{PCI}^{-1.539} - 0.2506 \quad (4.28)$$

where:

PREPCST = cost to prepare pavement for overlay (1981\$/sy)

PCI = current pavement condition index of feature  
between limits of 30 and 100

#### 4.3.5 Dynamic Programming Computer Outputs

Execution of the computerized dynamic programming model optimizes project level major rehabilitation activity plans. The model analyzes five plans for each feature. The first plan has no funds available for rehabilitation and only routine maintenance is applied. The remaining four plans are a function of funding level limitation. The four funding levels are equal intervals between what it costs to apply the cheapest activity (overlay with 2 inches of asphaltic concrete) at the beginning of the analysis period and the most expensive activity (reconstruction with portland cement concrete) inflated to the end of the analysis period.

The program finds the particular set of activities, and their schedules, that maximizes the area under the utility weighted PCI versus time curve subject to the major constraint of a fixed funding level. Figure 4.11 is an example of the output from this program. Since the output was designed as merely input into the network analysis portion of this research, it incorporates minimal user labeling. Furthermore, the output contains only those plans for each feature that are unique; duplicate plans are eliminated.

The output includes:

- 1) Base and feature name
- 2) Total benefit or performance of entire plan (area under curve)
- 3) Total cost of plan in dollars
- 4) TFW, total feature worth, relative value of feature to user
- 5) Decision (selected activity), cost of decision, accumulated benefit (area), and PCI, all as a function of age

For a typical airfield, an average of 3 plans per feature are generated for approximately 150 features. These are optimized plans, that is, the area under the utility weighted PCI versus time plot has been maximized with constraints, the most important of which are specified funding limitations over the span of the analysis period. Note that all costs are presented in present worth dollars. The decisions are indexed as 1, 2, 3, 4, and 5 and the same as explained in

```

*****
*EXAMPLE* R01A
  BASE  FEATURE      BENEFIT      COST      TFW
                    1127.      0.      48170.
  AGE  DECISION      COST  BENEFIT  PCI
  0.  1.             0.      0.      65.
  2.  1.             0.      164.    62.
  4.  1.             0.      317.    58.
  6.  1.             0.      460.    54.
  8.  1.             0.      592.    50.
 10.  1.             0.      712.    45.
 12.  1.             0.      820.    41.
 14.  1.             0.      916.    36.
 16.  1.             0.      999.    31.
 18.  1.             0.     1069.    26.
 20.  1.             0.     1127.    21.
*****

*EXAMPLE* R01A
  BASE  FEATURE      BENEFIT      COST      TFW
                    2104.     1196 82.    48170.
  AGE  DECISION      COST  BENEFIT  PCI
  0.  1.             0.      0.      65.
  2.  1.             0.      164.    62.
  4.  3.             1196 82.    420.    97.
  6.  1.             1196 82.    666.    93.
  8.  1.             1196 82.    903.    89.
 10.  1.             1196 82.   1130.    86.
 12.  1.             1196 82.   1347.    82.
 14.  1.             1196 82.   1553.    78.
 16.  1.             1196 82.   1748.    74.
 18.  1.             1196 82.   1932.    69.
 20.  1.             1196 82.   2104.    65.
*****

*EXAMPLE* R01A
  BASE  FEATURE      BENEFIT      COST      TFW
                    2294.     800000.    48170.
  AGE  DECISION      COST  BENEFIT  PCI
  0.  1.             0.      0.      65.
  2.  2.             800000.    258.    98.
  4.  1.             800000.    510.    96.
  6.  1.             800000.    755.    93.
  8.  1.             800000.    995.    91.
 10.  1.             800000.   1229.    89.
 12.  1.             800000.   1456.    86.
 14.  1.             800000.   1676.    84.
 16.  1.             800000.   1889.    81.
 18.  1.             800000.   2096.    78.
 20.  1.             800000.   2294.    76.
*****

```

Figure 4.11 Example Output From Dynamic Programming Computer Program for One Feature



Paragraph 4.3.1.

On the average, the computer program takes 3 central processing seconds per feature to generate the five plans on the University of Illinois Cyber 175 computer.

4.4 Summary

This chapter explained the dynamic programming procedures as they applied to project level optimization and discussed the mechanics of the procedures used in this research. The next chapter introduces the decision process of long range network level optimization.

## CHAPTER 5

## LONG RANGE NETWORK LEVEL OPTIMIZATION

5.1 General

This chapter discusses and models the decision process used by pavement engineers to develop long range major rehabilitative plans for entire systems of pavement sections. The chapter includes: an explanation of airfield systems (networks), decision process description, adaption of zero-one integer linear programming to the decision process, a specification of the optimization criterion and optimization constraints, and an explanation of the specific integer programming method used to obtain the optimal decisions.

## 5.2 Airfield Pavement Systems (Networks)

Network level planning involves considering several long range rehabilitation projects for each feature on the airfield. Although each of these projects may be optimal for a particular feature, there still remains the problem of selecting the best of these projects to satisfy the overall needs of the using aircraft as much as possible within the bounds of a limited budget for the entire network. Using long range network level optimization, airfield pavement engineers can select the best set of long-range projects for the network.

### 5.2.1 Airfield Pavement Network Definition

Definition of an airfield pavement network is common to both military and civilian airfields. An airfield pavement network is a grouping of two or more airfield pavement features. A network can consist of only a portion of an airfield, i.e., runway or an apron, or an entire airfield, complete with all the features including all the aprons, taxiways, and runways. Still a third definition groups several distinct airfields many miles apart into a network. These network groups can be located statewide, command wide, country wide or scattered throughout the world.

For the most part, a network level analysis encompasses only those pavement features under the control of a specific decision authority. One airfield would generally not conduct a network analysis for itself combined with another airfield not under their control. Yet on the other hand, a governing agency responsible for several airfields might justifiably include all the features on all the airfields within their jurisdiction into their network analysis.

#### 5.2.2 Air Force Network Definitions

The U.S. Air Force command structure is logically set up for networks defined in several ways. First, individual airfields constitute the most prevalent network. Next, the Air Force is divided in separate operating commands with jurisdiction over airfields spread throughout the world. These command divisions could delineate a second level of networks in the Air Force. Lastly, Air Force headquarters reserves the highest level of funding approval for itself as it directly petitions for funds from the Congress. Therefore, another definition of a network could be all airfields in the Air Force.

Summarizing, the Air Force has three basic network levels to which optimization techniques could be applied:

- 1) base
- 2) command
- 3) Air Force wide

### 5.3 Network Level Decision Process

Airfield pavement engineers are faced with complex decision process when developing long range network level major rehabilitation plans. At this level, they must select from a list, those projects that best satisfy the needs of the user within the bounds (constraints) placed upon them (usually by the user). These might include, but are not limited to:

- 1) budget limitations (included)
- 2) relative value of features to user (included)
- 3) quality of rehabilitative activity to feature (included)
- 4) political influence on affected features
- 5) operational impact on timing of rehabilitation activity

#### 5.3.1 Decision Process Description

At the network level, the best projects must be selected within a given funding limit. One method for selecting the best projects can be determined by prioritizing the features according to user needs. With only one project per feature (determined by a decision tree) the projects can be ranked according to user needs using the feature prioritizing. Budgets can then be allocated down the list until funds are depleted. However, this decision process does not consider:

- 1) Relative usefulness to user between features in network.
- 2) Relative structural benefit of activities to a feature between projects of the same feature and between projects of different features.

Pavement engineers have difficulty in manually selecting the best set of projects given a limited amount of money, because there are too many possible combinations of projects for them to analyze. Each combination provides a corresponding level of satisfaction to the user and to the pavement structure. To best spend the limited funds, the selected projects should maximize (optimize) the level of satisfaction for both of these needs (user and structure). Using OR techniques, the set of projects can be selected so that the highest possible satisfaction is achieved.

### 5.3.2 Network Level Decision Variables

There is only one type of decision variable in the model used to solve the network level optimization problem: there is one variable of this type for each alternative project for each feature. In the case of 150 features averaging three alternative projects per feature, there would be 450 decision variables in the problem. These variables are constrained by definition to take on the value of either zero or one. If a decision variable takes on the value one, then the project is selected. If it is zero, then it is not selected.

### 5.3.3 Network Level Optimization Criterion

The network level procedures developed in this research reflect long range planning because they select among projects already optimized over a long analysis period. The network level decision process does not differentiate time as a variable in the analysis. If the feasible projects reflected activities scheduled for the current year, then the network optimization would also only determine what to do for the current year. The network analysis procedure meets the future needs only if the projects subject to selection, are long range plans.

The network optimization criterion is a function of two parameters:

- 1) Importance of feature to the user
- 2) Benefit of the project to the structural performance of the feature.

#### 5.3.3.1 Importance of Feature

The total feature worth (TFW) is the importance or value placed upon a feature by the user. TFW is a function of: pavement type, pavement need, using aircraft type, using aircraft mission, and the number of aircraft by type and mission (previously defined in Chapter 3). This parameter quantifies the value of one feature relative to

another. Features need not be adjacent or even located on the same airfield. TFW is more than just a prioritized ranking of the most important feature to the least important feature. Its magnitude, as compared to each other, signifies the relative value of each feature to the user. If the TFW of a feature is twice that of another, then the value of the first feature to the user is twice that of the other.

TFW is computed for each feature considering the same data used for the development of long range rehabilitative plans at the project level. The actual TFW value for each feature is the subjective opinion of the author based on his six years experience as an Air Force pavement engineer.

#### 5.3.3.2 Structural Benefit to Feature

The structural benefit of the project to the feature (performance) is defined as the area under the utility weighted PCI versus time curve. This parameter, generated from the project level optimization process, represents the structural benefit to a feature from a specific set of rehabilitated activities. It is not merely a prioritized ranking of projects from the same feature, but it indicates the relative performance of the scheduled activities of projects from not only the same feature but also different features.



#### 5.3.3.3 Optimization Criterion

The optimization criterion in this research uses a combination of TFW and structural performance. Using either alone would neglect important considerations measured by the other parameter. Network plans optimized with only TFW would not consider structural consequences, either positive or negative, with different levels of funding. Additionally, long range network plans optimized with just structural performance would not consider the needs of the user as it selected projects. Conceivably, if structural performance alone were used, rarely used pavement features could receive more activity than an important highly used feature.

The optimization criterion, used in this research, is the TFW weighted structural performance. For each project in the network analysis, the product of TFW and structural benefit is computed and represents its contribution, if selected, to the overall objective.

#### 5.3.4 Network Level Optimization Constraints

For this research, two types of constraints were included in the network level optimization model. First and most importantly, the selected plans must not exceed a pre-established funding limit. And secondly, only one project per feature should be included in each

selected plan. Operational constraints (i.e., pre-specified features must either be selected or denied activities as a unit) could easily be added, but are not included here.

#### 5.4 Zero-One Integer Linear Programming Model

The decision variables in many problems must sometimes be limited to integer values. For example, people, machines, animals, cars, trucks, etc. can only be allocated in whole (integer) quantities. Integer optimization problems with only linear functions in the model are classified as integer linear programming problems. Further limitations can arise if the decision variables represent yes or no decisions. For example, such a decision variable could represent the selection of a specific policy. The decision variable is not only restricted to being an integer, but it is also restricted to only two values, zero or one (zero means no and one means yes). This type of integer programming problems with zero-one decision variables and linear functions is called zero-one integer linear programming (20).

In this research, the network level decision process is modeled as a zero-one integer linear programming problem. The decision variables represent the projects for all the features in the network. The values for each decision variable can only be zero or one, where zero means the project was not selected and one means the project was selected.

Modeling the network level decision process in this manner permits the selection of projects that maximizes the objective function (performance criteria) while maintaining a pre-established budget. However, obtaining an optimal solution by integer programming techniques is infeasible because most problems will contain too many decision variables to be solved in a reasonable amount of computer time. Therefore, a heuristic solution process has been used to obtain solutions which are generally close to optimal.

#### 5.5 Zero-One Integer Linear Programming Model of Network Decision Process

The zero-one integer linear programming model (here after referred to as the IP model) is composed of the objective function and constraints. These two parts are mathematical expressions of the decision variables (long long range major rehabilitative projects to undertake).

##### 5.5.1 Objective Function

The objective function of the network level decision process can be modeled as:

Maximize:

$$\sum_i \sum_j X_{ij} * P_{ij} * TFW_i \quad (5.1)$$

where:

- $X_{ij}$  = decision variable of the  $j$ th project and  $i$ th feature
- $P_{ij}$  = performance of the  $j$ th project and  $i$ th feature  
(area under utility weighted PCI curve)
- $TFW_i$  = total feature worth of the  $i$ th feature
- $i$  = feature counter
- $j$  = project counter

The product of the parameters  $P_{ij}$  and  $TFW_i$  represent both the structural performance of the activities in the project to the feature and the relative need of the project's feature to the user.  $P_{ij}$  and  $TFW_i$  are both determined during the project level analysis as explained in Chapter 3.

#### 5.5.4 Constraint Functions

Three constraints are included in the model used in this research. First the total cost of the selected projects must not exceed a pre-established limit. This can be mathematically expressed as follows:

$$\sum_i \sum_j X_{ij} * C_{ij} \leq \text{MAXCOST} \quad (5.2)$$

where:

- $X_{ij}$  = decision variable of the  $j$ th project and  $i$ th feature
- $C_{ij}$  = cost of the  $j$ th project and  $i$ th feature

For all projects selected ( $X_{ij} = 1$ ), this summation will determine the total network cost.

Secondly, it is necessary to mathematically restrict selection to no more than one project per feature. This can be accomplished with:

$$\sum_j X_{ij} \leq 1 \text{ for all } i \quad (5.3)$$

where:

$X_{ij}$  = decision variable of the  $j$ th project and  $i$ th feature

This expression limits the selection of no more than one project per feature, but the functions' inequality does not force the model to select a project for every feature.

Lastly, the requirement that the decision variables are limited to the integer values of zero or one, mathematically restricts the optimal solution to whole projects.

## 5.6 IP Model Solution

Because of the limitation of the computational capabilities of current integer programming methods, the zero-one integer model in this research was solved using a highly efficient heuristic (36). Resource allocation problems are commonly modeled with zero-one integer programming. Solving zero-one integer models is difficult with a large

number of decision variables because such problems can not be solved in a reasonable amount of time (34,20,36,37). Since the network level allocation problems developed in this research have a large number of decision variables, it is infeasible to solve them optimally. Heuristics have been developed which do not guarantee an optimal solution, but which provide a solution reasonably close to optimal.

#### 5.6.1 Toyoda Algorithm

Toyoda's heuristic for obtaining approximate solutions to zero-one programming problems is highly successful in determining optimal solutions to specific classes of problems (38,39). In general, zero-one integer programming problems solvable with this algorithm can be described as follows:

$$\text{MAXIMIZE: } Z = \sum_{i=1}^m K_i * X_i \quad (5.4)$$

$$\text{SUBJECT TO: } \sum_{i=1}^m H_{ij} * X_i \leq L_j \text{ for } j = 1, 2, \dots, n \quad (5.5)$$

$$\text{AND: } X_i = 0 \text{ or } 1 \text{ for } i = 1, 2, \dots, m \quad (5.6)$$

where:

$Z$  = objective function value

$K_i$  = performance of project  $i$

$X_i$  = decision variable representing project  $i$

$H_{ij}$  = magnitude of resource  $j$  required for project  $i$

$L_j$  = upper limit of resource  $j$

$n$  = number of restricted resources

$m$  = number of projects

$i$  = index of projects

$j$  = index of resources

with:

$$K_i > 0$$

$$H_{ij} > 0$$

$$L_j > 0$$

when:

$X_i = 1$  then project is selected

$X_i = 0$  then project is not selected

A later section contains an explanation of the mechanics of the algorithm and its performance in determining the optimal solution.

The network level project selection model is within the scope of the Toyoda algorithm. Using it, a set of projects can be identified that maximizes the satisfaction of the user and the needs of the pavement structure.

### 5.6.2 Computer Program Description

A computer program was written for using Toyoda's algorithm in selecting the optimal set of projects for a network that maximizes the product of the project's structural performance (area) and the effected feature's value to the user (TFW). The program was written in CDC's Fortran V with 826 lines and 15 subroutines supporting the main program. Figure 5.1 is a program flow chart showing the major elements of the Toyoda algorithm for solving large IP problems of the appropriate form.

After the problem data are entered into the program a candidate project list is established. If candidate projects are present then effective gradients (defined in next section) for all the projects are computed. The project with the maximum effective gradient is selected as part of the optimal solution. Model constraints are checked, and a new candidate project list is established. If there are projects left to consider then the gradients are again determined for each project, the project with maximum gradient is selected, etc. until there are no candidate projects remaining. The results of the algorithm are the selected projects from each interaction.



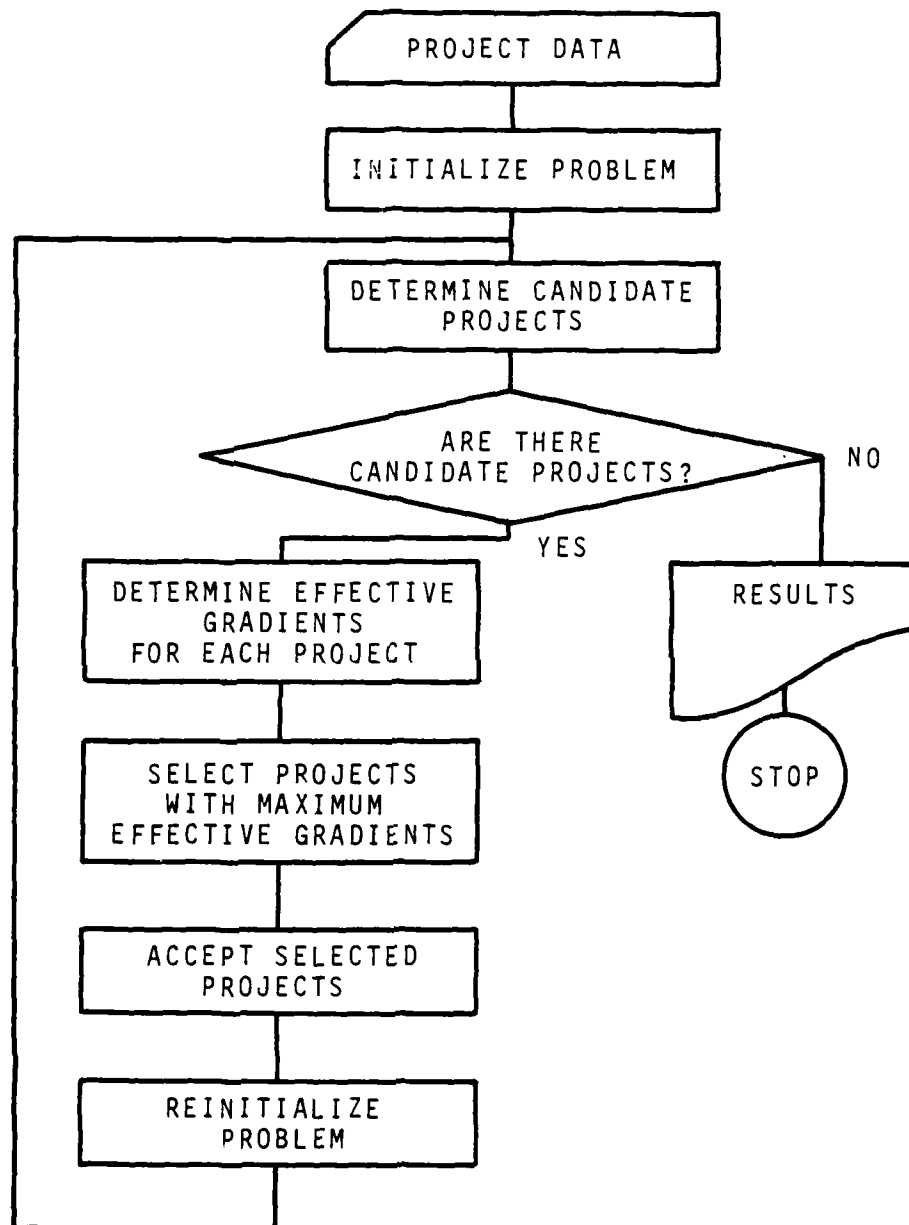


Figure 5.1 Computer Program Flowchart for Toyoda Algorithm

### 5.6.3 Algorithm Explanation

Toyoda's algorithm is a simple and quick method for obtaining approximate solutions to large scale zero-one programming problems of a certain form. The method does not use enumeration, as do most other methods, but instead uses a measure of preferability (effective gradient) to change the decision variables from zero to one (selected projects) (39).

The preferability of each feasible project is the effective gradient or the unit gain (as measured by the objective function) per the resources expended. When the problem contains only one resource it is easy to find the preferability of each project. When more than one resource (model constraint) exists, it is not easy to evaluate and compare between projects the unit gain in the objective per resources expended. Toyoda's algorithm uses a penalty vector to establish a scalar quantity representing the gain in objective per all the resources expended. This effective gradient is then used to select a project for the final solution. The effective gradient for the remaining projects changes as projects are selected one at a time.

#### 5.6.4 Computer Program Inputs

Data for the computer program can be input in three ways: interactively by the user, a previously interactively generated data file, and a condensed data file generated by the computer based on output from the project level optimizations.

##### 5.6.4.1 Interactive User Input

The program can optionally interactively prompt the user for all the information to execute the algorithm. For small problems (small networks) this method is satisfactory. For large problems, interactive active data input is time consuming and tedious.

The program prompts for the following information:

- 1) Problem title
- 2) Number of projects
- 3) Number of resources (constraints)
- 4) Project requirements of each resource
- 5) Resource limits
- 6) Project response (objective function contribution)
- 7) Output format instructions

#### 5.6.4.2 Interactively Generated Data File Input

As the user responds to the prompts during an interactive input session, the program automatically generates another computer data file with all the input data. At a later session, the user can prompt the computer to read all the input data from this previously generated file. In this manner the user can save time and edit the data file for mistakes and/or make changes for another analysis.

#### 5.6.4.3 Computer Generated Condensed Data File Input

The two previous methods of data input into the Toyoda algorithm are time consuming and tedious, for even normal sized networks. To input normal and larger sized network problems efficiently, a computer program was written that reads the data from a file generated by the project level dynamic programming algorithm and creates a condensed data set for the Toyoda program. All input parameters for the Toyoda program are established except the network funding limit. The network funding limit is interactively inputted by the user to preclude running the condensing program repeatedly for analysis of the same network at many different funding levels.

The condensing program is written in CDC's Fortran V and has 384 lines with 5 subroutines supporting the main program. Figure 5.2 is a flowchart depicting the main functions of the computer program.

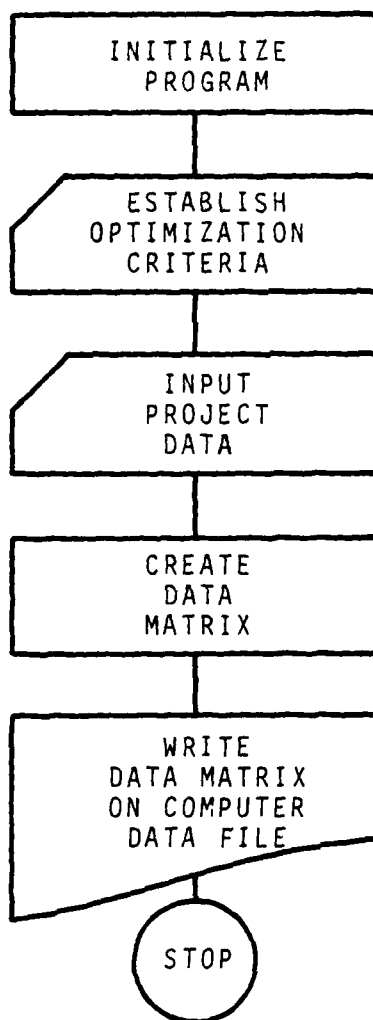


Figure 5.2 Computer Program Flowchart for Condensing Project Level Dynamic Programming Data for Toyoda Algorithm

#### 5.6.5 Toyoda Computer Program Outputs

The Toyoda computer program identifies those projects that optimize the project's structural performance and affected features' value for the entire network subject to a pre-established funding limit in present worth dollars. The same condensed data can be rerun at different funding levels established by the user. Figure 5.3 is an example of the output from the Toyoda algorithm program. Since this information is used as input into a report generating program it currently has minimal user labeling. The output contains the following information:

- 1) Problem title with optimization criteria
- 2) Listing of selected projects
- 3) Objective function value of selected projects only
- 4) Resource 1 limitation (network funding limit)
- 5) Resource 1 used (amount of network funding limit expended on this set of projects)

The index number identifying each project is assigned in the condensing program and is interpreted in the report generating program discussed next.

The condensing program requires little computer time to execute. For a network with approximately 300 projects on 100 features, the program takes between 3 and 4 central processing seconds to generate the condensed data set on the University of Illinois Cyber 175 computer.

## EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW\*PERFORMANCE

## SELECTED PROJECTS

1  
5  
7  
11  
13

## MAXIMIZED OBJECTIVE FUNCTION VALUE

429306 570.

## RESOURCE 1 LIMITATION

750000.

## RESOURCE 1 USED

366428.

Figure 5.3 Output Example for Toyoda Algorithm

The Toyoda algorithm requires more time and it is a function of the pre-established funding limit. Figure 5.4 depicts the central process time as a function of funding limit.

### 5.7 Network Analysis Report

A computer program was written to generate a series of three reports for each level of network funding based on the results of the computer programs for the project and network level analyses. The program reads from two files (one each from the dynamic programming and Toyoda programs) and compiles the results into a useable format. For each network funding limit the following reports are compiled:

- 1) Selected Project Listing
- 2) Features Without Projects
- 3) Network Summary

The report program is written in CDC's Fortran V and consists of 838 lines with 12 subroutines supporting the main program.

#### 5.7.1 Selected Project Listing

Figure 5.5 is an example of the Selected Project Listing (SPL) report for the same problem discussed in a later section. For each



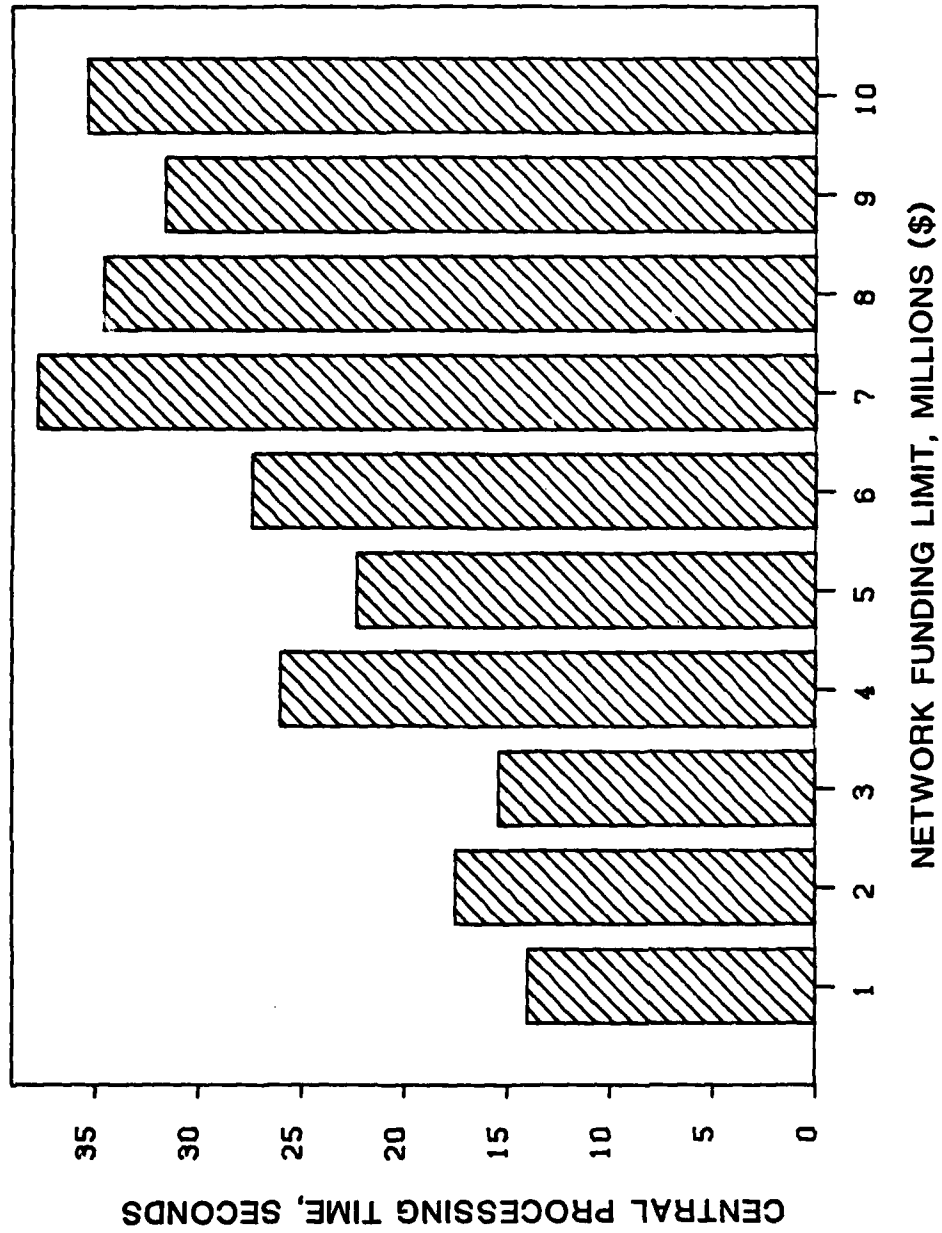


Figure 5.4 Central Processing Time on University of Illinois Cyber 175 Computer Versus Network Funding Level Limit

```

*****
*
*   SELECTED PROJECT LISTING
*
*   NETWORK OPTIMIZATION
*
*****
*
*   DECISION LEGEND
*
*   R/M = ROUTINE MAINTENANCE
*   R/C = RECONSTRUCT
*   O/L2 = OVERLAY WITH 2" AC
*   O/L4 = OVERLAY WITH 4" AC
*   O/L6 = OVERLAY WITH 6" AC
*
*****

```

NETWORK DESCRIPTION:           EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW\*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH):   250000

AMOUNT SPENT(PRESENT WORTH):   246746

OBJECTIVE FUNCTION VALUE:   327956890

*****												
BASE	FEATURE	TOTAL COST	BENEFIT	WORTH								
*EXAMPLE*	R03A	185435	2214	48170								
	TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
	PCI	80	78	76	74	72	70	98	96	95	93	91
	DECISION	R/M	R/M	R/M	R/M	R/M	O/L4	R/M	R/M	R/M	R/M	R/M
	COST(\$)	0	0	0	0	0	185435	0	0	0	0	0
-----												
BASE	FEATURE	TOTAL COST	BENEFIT	WORTH								
*EXAMPLE*	T01A	23512	2049	41170								
	TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
	PCI	60	57	96	92	88	84	80	76	71	66	61
	DECISION	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M	R/M	R/M
	COST(\$)	0	23512	0	0	0	0	0	0	0	0	0
-----												
BASE	FEATURE	TOTAL COST	BENEFIT	WORTH								
*EXAMPLE*	T03C	17951	2035	22810								
	TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
	PCI	75	73	71	68	95	89	84	79	74	68	63
	DECISION	R/M	R/M	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M
	COST(\$)	0	0	0	17951	0	0	0	0	0	0	0
-----												
BASE	FEATURE	TOTAL COST	BENEFIT	WORTH								
*EXAMPLE*	T05A	19848	2199	41170								
	TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
	PCI	75	73	70	68	97	95	92	89	86	84	81
	DECISION	R/M	R/M	R/M	O/L2	R/M	R/M	R/M	R/M	R/M	R/M	R/M
	COST(\$)	0	0	0	19848	0	0	0	0	0	0	0
-----												

Figure 5.5 Selected Project Listing Example

level of network funding in the analysis, an SPL is compiled. It lists all the projects that the Toyoda algorithm selected. Each project is listed with the following data:

- 1) Base and feature name
- 2) Total cost of project in present worth dollars
- 3) Benefit, defined as the structural performance of the activities during the analysis period (total area under the utility weighted PCI versus time plot)
- 4) Worth, defined as the relative value of the affected feature to the user (function of the aircraft type, mission and number, plus the pavement type and need).
- 5) PCI, pavement condition index as a function of time
- 6) Decision, optimized activities spanning the analysis period
- 7) Cost, expenditures for activities during the analysis period in present worth dollars

Preceding the project listings, the following network analysis data is anoted:

- 1) Report title
- 2) Decision legend
- 3) Network description with optimization criteria
- 4) Network funding limit
- 5) Amount spent in this listing on present worth dollars
- 6) Objective function, value of the total network plan.

### 5.7.2 Features Without Projects Listing

Figure 5.6 is an example of the Features Without Projects (FWP) report for the sample problem. The FWP report lists all the features in the network that did not receive any work from the selected projects and the consequences of these decisions on the specific features. Each feature is listed with the following data:

- 1) Base and feature name
- 2) Benefit, defined as the structural performance of the feature with only routine maintenance during the analysis period (total area under the utility weighted PCI versus time curve)
- 3) Rel Value, same as worth, defined as the relative value of the feature to the user (function of the aircraft type, mission, and number, plus the pavement type and need)
- 4) PCI, pavement condition index as a function of time

Note as with the previous report, the listing is preceded by the network description, funding limit and amount spent. As anoted on the report, those features whose PCI falls below 40 are astericked and flagged, emphasizing the serious condition of these features to the using pavement engineers. As with the SPL, a FWP is also generated at each network funding level.

```

*****
*
* * FEATURES WITHOUT *
*
* * PROJECTS *
*
*****

NETWORK DESCRIPTION:      EXAMPLE PROBLEM WITH OPTIMIZED WITH TFW*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH):      250000

AMOUNT SPENT(PRESENT WORTH):      246746

FEATURES FALLING BELOW PCI OF 40 ARE FLAGGED AND PCI'S ARE ASTERISKED

*****
BASE   FEATURE  BENEFIT  REL VALUE  PCI BY YEAR
*****
<40  *EXAMPLE*  R01A  1127  48170  65  62  58  54  50  45  41  36* 31* 26* 21*
      *EXAMPLE*  R02C  1654  48170  75  73  71  68  66  64  62  60  58  55  53
<40  *EXAMPLE*  T02A  1128  41170  65  62  58  54  50  45  41  36* 31* 26* 21*
      *EXAMPLE*  T04C  2032  22810  85  84  82  81  80  78  77  76  75  73  72
      *EXAMPLE*  A01B  2007  16420  85  84  82  81  79  78  76  75  73  71  70
*****
<40  *EXAMPLE*  A02B  1089  22750  60  57  53  50  46  43  39* 36* 32* 29* 25*

```

Figure 5.6 Features Without Projects Example

### 5.7.3 Network Summary Report

Figure 5.7 is an example of Network Summary (NS) report. The NS report is a summary of data for a specific funding level of the network analysis. Again it identifies the report with a network description, funding limit and amount spent. Then the following information is compiled as a function of time during the analysis period:

- 1) PCI, an average pavement condition index weighted with total feature worth (TFW)
- 2) Cost, amount spent on the network in present worth dollars
- 3) Accumulated Cost, the summed total amount spent on the network in present worth dollars
- 4) New Features w/PCI 40, the number of additional that have just fallen below a PCI of 40
- 5) Poor Features (PCI 40), the total number of features in the network with a PCI less than 40
- 6) Benefit, total benefit from all the features in the network during that time interval
- 7) Accumulated Benefit, the summed total benefit from all the features in the network

Note, Benefit is defined as the area under the utility weighted PCI versus time plot for each feature over the entire analysis period or during a specific interval of time.

\*\*\*\*\*  
 \*  
 \* NETWORK SUMMARY \*  
 \*  
 \*\*\*\*\*

NETWORK DESCRIPTION: EXAMPLE PROBLEM WITH OPTIMIZED WITH TEN\*PERFORMANCE

NETWORK SPENDING LIMIT(PRESENT WORTH): 250000

AMOUNT SPENT(PRESENT WORTH): 246746

\*\*\*\*\*

TIME(YEARS)	0	2	4	6	8	10	12	14	16	18	20
PCI(WEIGHTED)	71	69	71	68	71	67	68	65	62	58	55
COST(PRESENT WORTH)MILLIONS	0.00	.02	0.00	.04	0.00	.19	0.00	0.00	0.00	0.00	0.00
ACCUM COST,MILLIONS	0.00	.02	.02	.06	.06	.25	.25	.25	.25	.25	.25
NEW FEATURES W/PCI <=40	0	0	0	0	0	0	1	2	0	0	0
POOR FEATURES(PCI <=40)	0	0	0	0	0	0	1	3	3	3	3
BENEFIT	0	1844	1887	1817	1910	1827	1823	1736	1650	1565	1475
ACCUM BENEFIT	0	1844	3731	5548	7458	9285	11108	12844	14494	16059	17534

\*\*\*\*\*

Figure 5.7 Network Summary Example

The report program generates all three listings for each level of network funding. It takes approximately 7 central processing seconds for a single funding level report on the University of Illinois Cyber 175 computer.

#### 5.8 Sample Airfield Application

As an illustration, a small sample airfield was analyzed with these procedures. The sample airfield has only ten features so the size of the problem does not hinder understanding the decision process (Figure 5.8). The inputs for each feature were extracted from real Air Force base features subjected to light load aircraft. All the feature data was run through the dynamic programming algorithm and these results were input into the Toyoda network analysis programs. All reports were generated for funding levels between zero and 3 million present worth dollars (at \$250,000 intervals). The resulting objective function (TFW weighted performance) values are plotted on Figure 5.9. As a comparison, the same sample airfield was managed manually as follows. Using three different condition levels (PCIs of 40, 60, and 80) a separate network analysis was completed. An activity (2 inch asphalt overlay) was scheduled for any feature on the sample airfield when its condition reached the pre-established minimum condition level (40, 60, 80 PCI). The analyses were carried out for 20 years (the same as for the Toyoda analyses). For each of the three analyses, the objective function value was calculated and plotted on Figure 5.9.



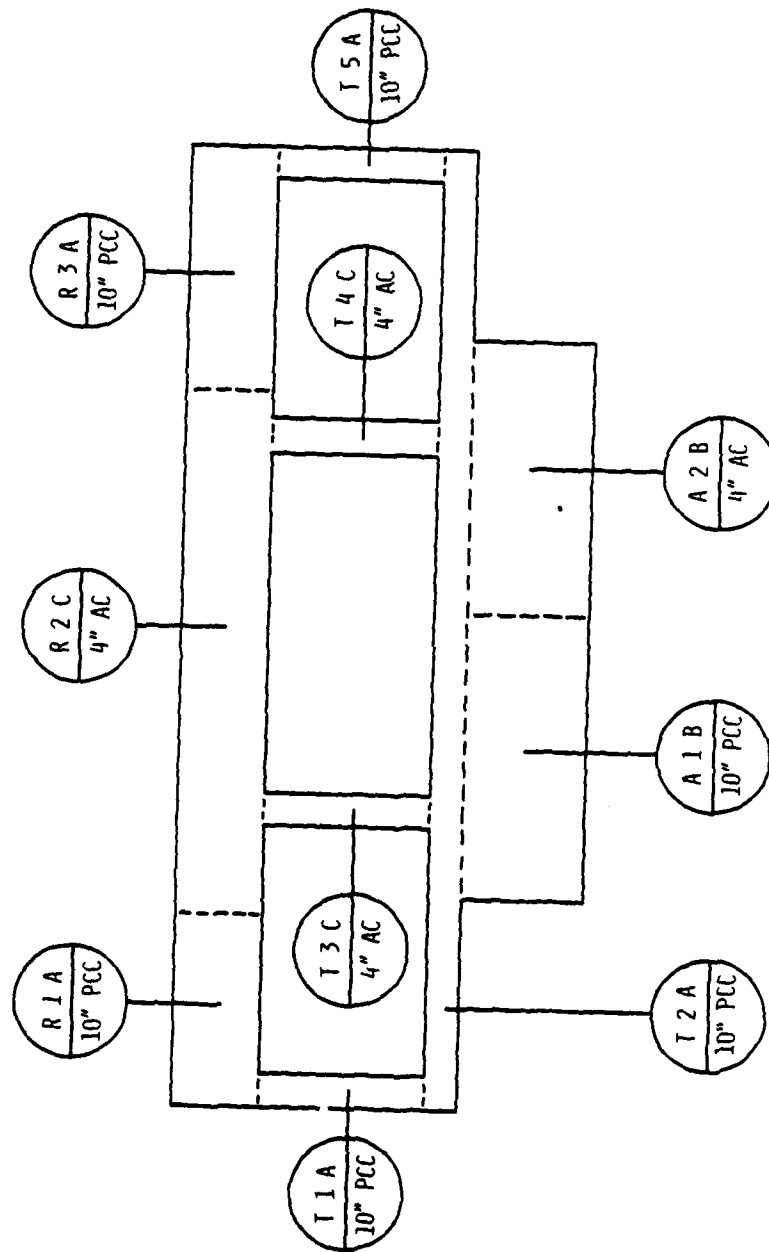


Figure 5.8 Layout of Example Airfield

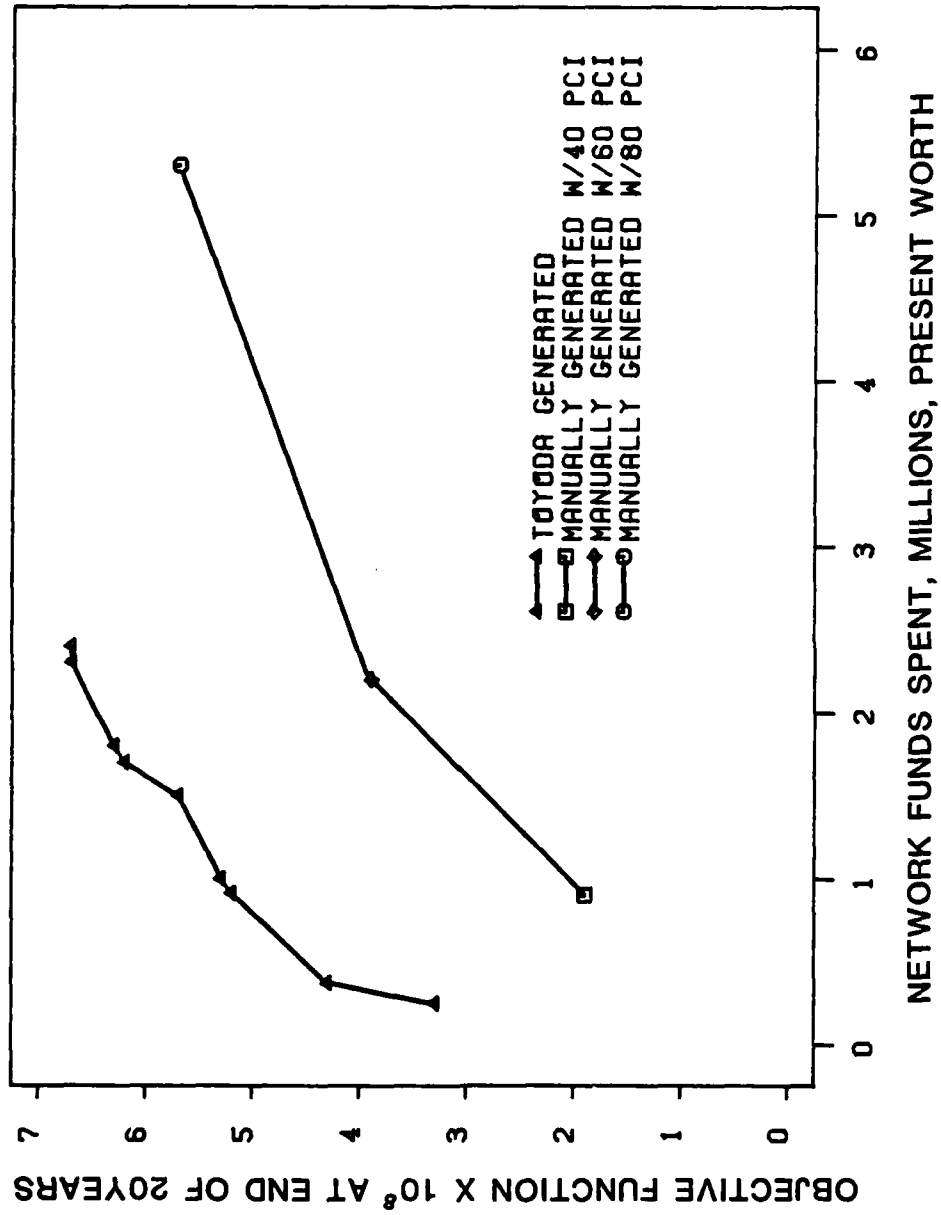


Figure 5.9 Objective Function Versus Network Funds Spent for Example Airfield

Note, that in each case, for the same amount of money spent, the methods developed in this research nearly double the objective function values obtained manually. Or, from another perspective, for any level of the objective function, the cost of the optimally selected projects were less than half the cost of the manually selected methods to achieve the same objective function value.

Examination and comparison of the results (which feature activities were scheduled at various funding levels) for both methods revealed several reasons for the vast differences illustrated in Figure 5.9.

- 1) Activity assignment was optimized at the project level for the method derived in this research.
- 2) Manual network analysis selected projects irrardless of the relative value of feature to the user.
- 3) Manual analysis also does not take into consideration the structural benefit (performance) of a selected activity schedule (project).

This small example illustrates the value of the programs developed in this research: they provide substantially better ways of spending the same money and/or maintaining an established condition for a reduced amount of money.

### 5.9 Summary

This chapter introduced the network level decision process by explaining airfield pavement networks, the decision process, use of zero-one integer programming, the optimization/constraint criteria for the network decision process, and solution by Toyoda's heuristic. A general discussion of the computer programs used in the network analysis included: Toyoda's algorithm, data condensing, and report generating. The next chapter discusses an application of the project and network level analysis procedures to McClellan Air Force Base.

## CHAPTER 6

## RESEARCH APPLICATION

6.1 General

In this chapter, the procedures described in the preceding chapters are applied to McClellan Air Force Base (MAFB), California. The entire process is presented from, the initial data collection through an analysis of the final reports.

McClellan AFB is located eight miles northeast of downtown Sacramento, California in the northern portion of the Great Valley of California (Sacramento Valley) and near the western edge of the Sierra Nevada foothills. The airfield pavements complex consists of a

north-south runway, parallel taxiway and eight connecting taxiways on the east side, five parking and maintenance aprons on the east side, five taxiways and three aprons on the west side, and several maintenance hanger/shelter access ramps located around the airfield. Figure 6.1 is a layout of the airfield with all the features identified (40).

## 6.2 Data Collection

Input data for the analysis were collected from several sources:

- 1) Airfield pavement evaluation report (40).
- 2) Pavement condition information from U.S. Air Force Logistics Command Engineering and Services Office at Wright-Patterson AFB, Dayton, Ohio.
- 3) Conversations with Air Force Logistics Command pavement engineer and McClellan AFB pavement engineer.
- 4) Airfield layout data from Air Force Engineering and Services Center, Tyndall AFB, Panama City, Florida.

Data were collected via telephone conversation, mail, and personal visit. The pavement condition information was obtained from a complete PCI survey of all the airfield features, stored on the command computer data system at Dayton, Ohio; and the airfield pavement evaluation information was obtained from reports located at Dayton, Ohio; Panama City, Florida; and the base, Sacramento, California.

The necessary data were extrapolated from these sources and coded for the University of Illinois Cyber 175 computer. Figure 6.2 is a sample of the coded data source file for McClellan AFB. The data by line are:

- 1) Base and feature name, pavement type.
- 2) Feature length, width and age.
- 3) If rigid then slab size, modulus of rupture, modulus of soil reaction, slab thickness, asphalt overlay thickness, current PCI, percent slabs replaced, freezing index, percent slabs patched, and average annual temperature.
- 4) If flexible the, number of layers in pavement, asphalt thickness, age of overlay.
- 5) If flexible then, layer type code, layer thickness, and layer CBR. (a line for each layer)
- 6) If flexible, current PCI, average annual temperature, freezing index.
- 7) Pavement use, pavement need.
- 8) Maximum asphalt overlay thickness, reconstructed pcc thickness, overlay cost per  $\text{yd}^2$  per inch thick, reconstruction cost per  $\text{yd}^2$ , reconstructed modulus of rupture, reconstructed modulus of soil reaction, reconstructed slab size.

After the feature property data have been coded into the computer, the dynamic programming algorithm is used to generate optimized long

```

*****
MCCLELLAN T10C FLEX
220 75 27
4 0 0
1 4 0
10 6 45
10 22 35
10 0 7
85 62 27
5 175000
6
11 23 6
15 23 6
16 23 12
14 22 8
15 22 12
14 22 6
32 41
6 10 2.40 57.33 700 350 20 20
*****
MCCLELLAN T11C RIGID
212 212 38
20 20 650 350 10 0 78 0 27 15.87 62 0
5 175000
6
11 23 6
15 23 6
16 23 12
14 22 8
15 22 12
14 22 6
32 42
6 10 2.40 80.71 700 350 20 20
*****
MCCLELLAN T12C RIGID
203 203 23
20 20 650 350 10 3 71 0 27 0 62 0
5 175000
6
11 23 6
15 23 6
16 23 12
14 22 8
15 22 12
14 22 6
32 42
6 10 2.40 80.71 700 350 20 20
*****

```

Figure 6.2 Abbreviated Data Source File for McClellan AFB



range major rehabilitation plans for each feature. The algorithm ran for 340 central processing seconds on the University of Illinois Cyber 175 computer. Figure 6.3 is an example of the output from this program for McClellan AFB. For each feature five funding levels were analyzed. As shown for feature R01A, on the figure, the first project for each feature is always limited to zero funding. Four other funding levels were also analyzed for each feature. Of the 416 projects generated for the 104 features at McClellan AFB, only 309 were saved for further analysis. The remaining were discarded as duplicates. The generated project data were reduced into a condensed data set for input in the Toyoda algorithm. The condensing program took less than 4 central processing seconds to extrapolate the important data from the dynamic programming generated listing and construct a data matrix for the Toyoda algorithm.

Using the condensed data from the dynamic program, the Toyoda program optimally allocates a pre-established funding limit among the candidate projects in order to fund those projects which maximize the TFW weighted structural performance. The Toyoda program was run for fourteen levels of network funding between zero and 25 million present worth dollars. An output, similar to Figure 5.3 (Chapter 5), was generated for each funding level. Each funding level output and the dynamic programming output were used as input into the network report program. Examples of the reports are shown on Figures 5.5, 5.6, and 5.7 (Chapter 5). Using the information produced in these reports, the consequences of varying network funding level can be made. All the

*****				
MCCLELLAN ROLA				
BASE	FEATURE	BENEFIT	COST	TFW
		1772.	0.	55878.
AGE	DECISION	COST	BENEFIT	PCI
0.	1.	0.	0.	80.
2.	1.	0.	205.	78.
4.	1.	0.	404.	76.
6.	1.	0.	598.	74.
8.	1.	0.	786.	72.
10.	1.	0.	967.	69.
12.	1.	0.	1142.	67.
14.	1.	0.	1311.	64.
16.	1.	0.	1472.	62.
18.	1.	0.	1625.	59.
20.	1.	0.	1772.	56.
*****				
MCCLELLAN ROLA				
BASE	FEATURE	BENEFIT	COST	TFW
		2207.	92989.	55878.
AGE	DECISION	COST	BENEFIT	PCI
0.	1.	0.	0.	80.
2.	1.	0.	205.	78.
4.	1.	0.	404.	76.
6.	1.	0.	598.	74.
8.	1.	0.	786.	72.
10.	1.	0.	967.	69.
12.	4.	92989.	1225.	98.
14.	1.	92989.	1479.	96.
16.	1.	92989.	1727.	94.
18.	1.	92989.	1969.	92.
20.	1.	92989.	2207.	90.
*****				
MCCLELLAN ROLA				
BASE	FEATURE	BENEFIT	COST	TFW
		2216.	137528.	55878.
AGE	DECISION	COST	BENEFIT	PCI
0.	1.	0.	0.	80.
2.	1.	0.	205.	78.
4.	1.	0.	404.	76.
6.	1.	0.	598.	74.
8.	1.	0.	786.	72.
10.	1.	0.	967.	69.
12.	5.	137528.	1226.	93.
14.	1.	137528.	1480.	97.
16.	1.	137528.	1730.	95.
18.	1.	137528.	1975.	93.
20.	1.	137528.	2216.	92.
*****				

Figure 6.3 Sample of Dynamic Programming Output for McClellan AFB

programs developed in this research were run for McClellan AFB. Approximately 830 central processing seconds were used for the base as itemized on Table 6.1.

### 6.3 McClellan AFB Application Graphs

Using the information on the report listings from the various funding levels, the consequences of specific funding levels can easily be seen. Figures 6.4, 6.5, 6.6, and 6.7 are constructed from data in the report listings at each level of network funding limit.

Figure 6.4, as expected has a smooth continuous increase in the objective function (TFW weighted structural performance) as a function of network funding limit. This graph amounts to relaxing the constraint of spending dollars and permits more projects to be funded.

Figure 6.5 plots the terminal weighted average network PCI as a function of network funding limit. It too, has a continuous increase on terminal PCI. Note that the first time the curve levels off, it occurs at a PCI corresponding to the constraint that no activities will be scheduled until the pavement reaches that level (in this case, 70 PCI).

Figure 6.6 plots the number of features that fall below a PCI of 40 by the end of the 20 year analysis period. There is a continuous decrease until the 10 million dollar limit. Analysis of the data

Table 6.1 Computer Usage Summary for McClellan AFB Application

COMPUTER USAGE SUMMARY  
FOR McCLELLAN AFB

Computer Program	Program Description	Central Processing* Time (Seconds)
DYNC	Dynamic Programing, generation of feature projects, 104 features	350
CONPRG	Condensing Program, consolidates DYNC output for Toyoda Program	4
TOY	Toyoda Program, Network allocation, run 14 times	375
REPORT	Network Report Program compile network reports, run 14 times	100
Total		<u>829</u>

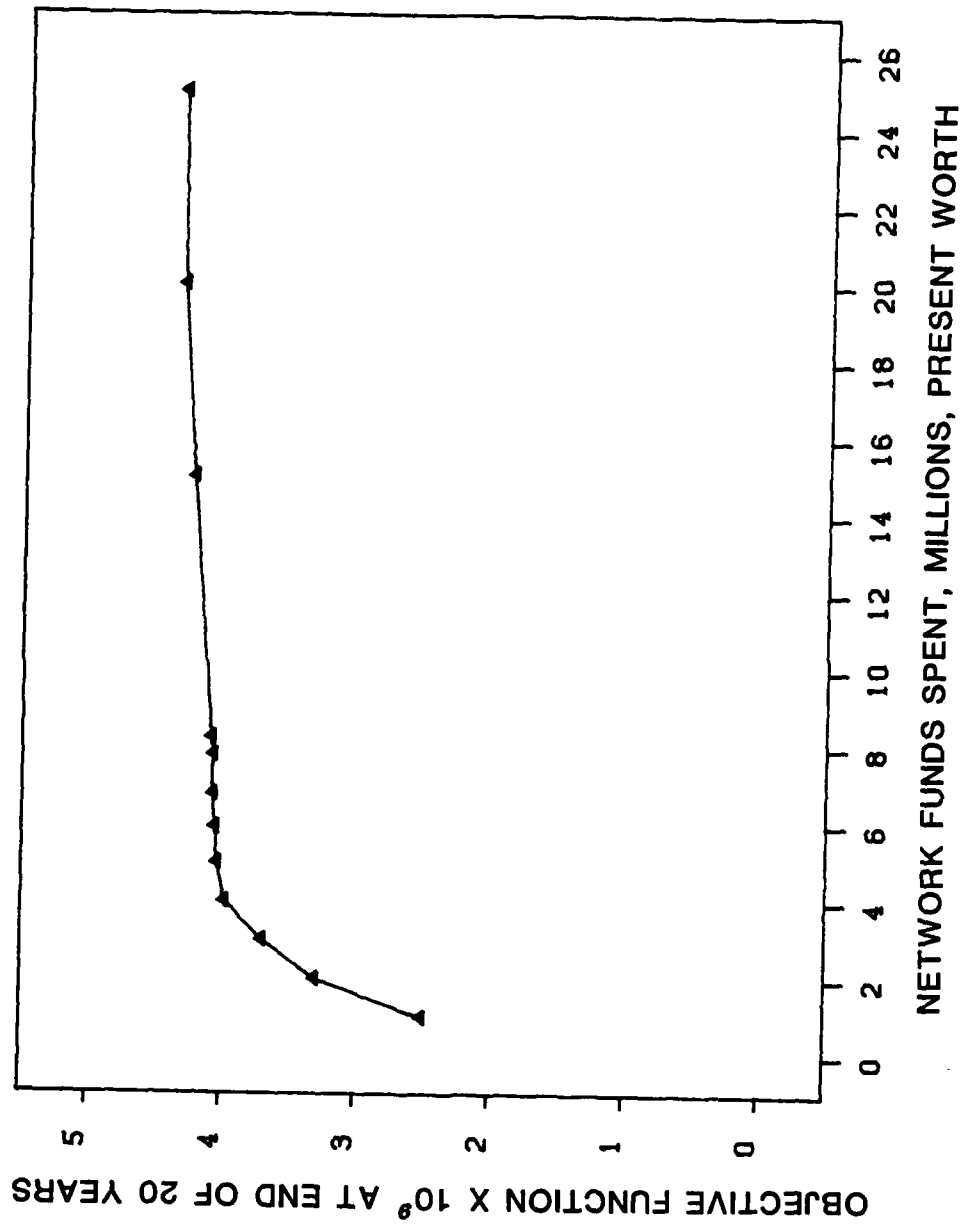


Figure 6.4 Objective Function Versus Network Funds Spent,  
McClellan AFB

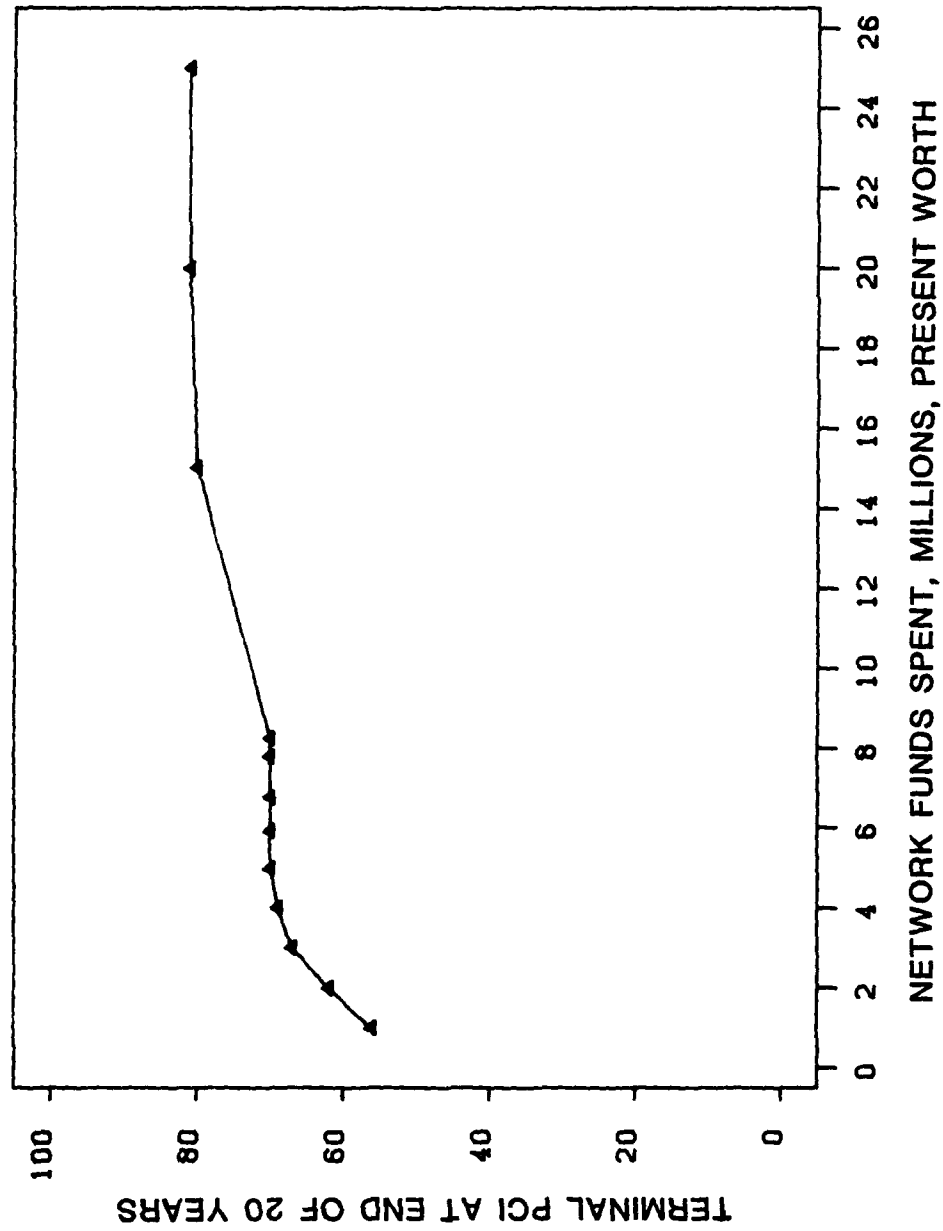


Figure 6.5 Terminal PCI at 20 Years Versus Network Funds Spent,  
McClellan AFB

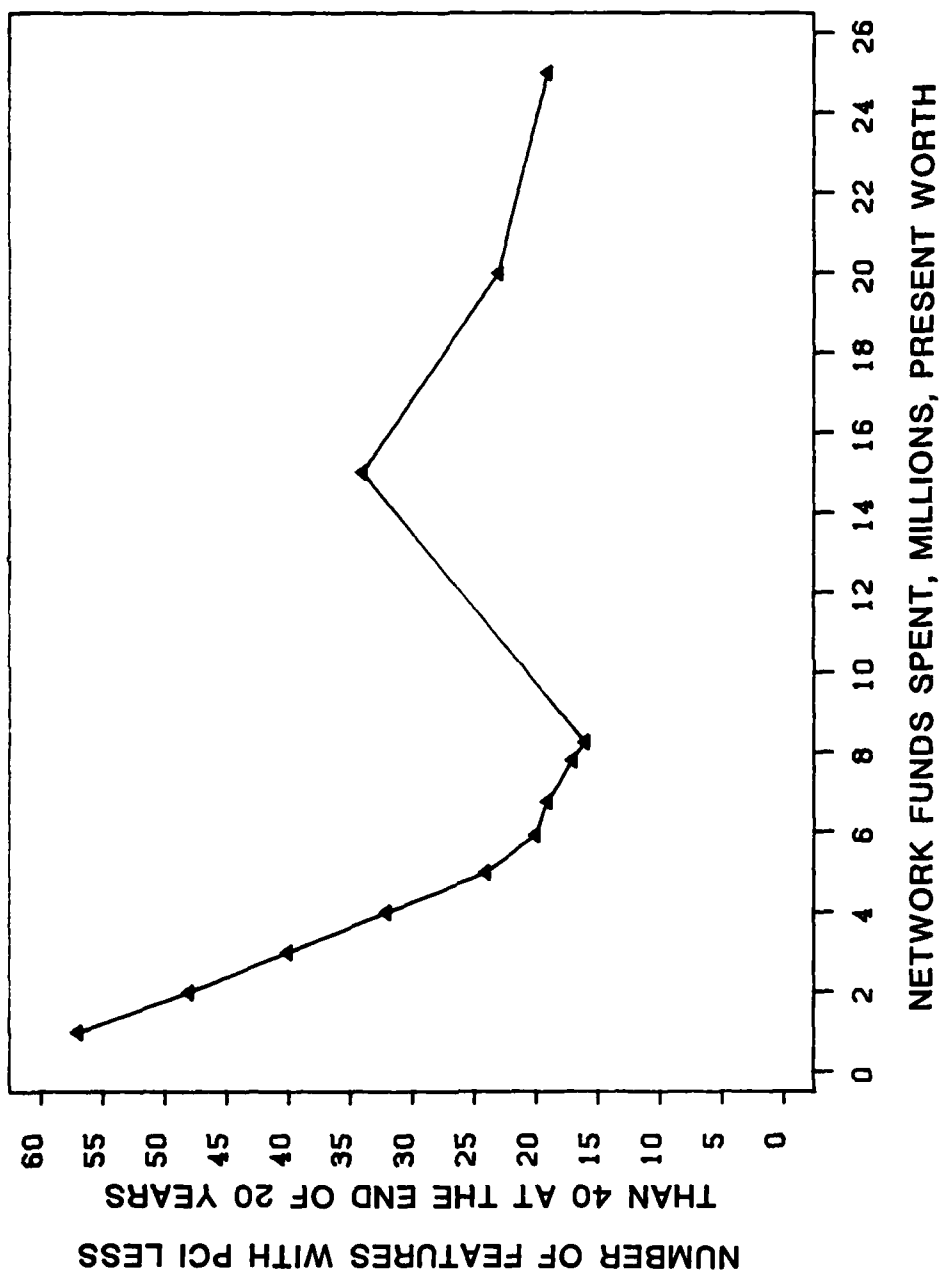


Figure 6.6 Number of Features with PCI Less Than 40 at End of 20 Years Versus Network Funds Spent, McClellan AFB

reveals that at this funding level all features with any value to the user have had projects funded. With additional network funding, the Toyoda algorithm identifies more gain to the objective function by funding more expensive projects for features having projects selected at lower levels of funding.

Figure 6.7 has the same discontinuity in its curve as it plots network performance (summation of projects performance) versus network funding limit. The decrease in performance with increased network funding (after 10 million) results from the TFW weighting in the objective function.

Figure 6.8 is a composite summary of Figures 6.4, 6.5, 6.6 and 6.7 showing on one graph the consequences to the network for various network funding levels. The region on the graph between 5 and 10 million, indicates a network funding where not only the objective function levels off but the other three network consequence indicators also level off.

#### 6.4 Application Discussion

With these graphs and reports, airfield pavement engineers can begin to effectively manage their pavement system (McClellan AFB) over the analysis period (20 years) for major rehabilitative activities. The graph of Figure 6.8 can be used to estimate what level of network funding would be the best for the airfield and hence they can determine



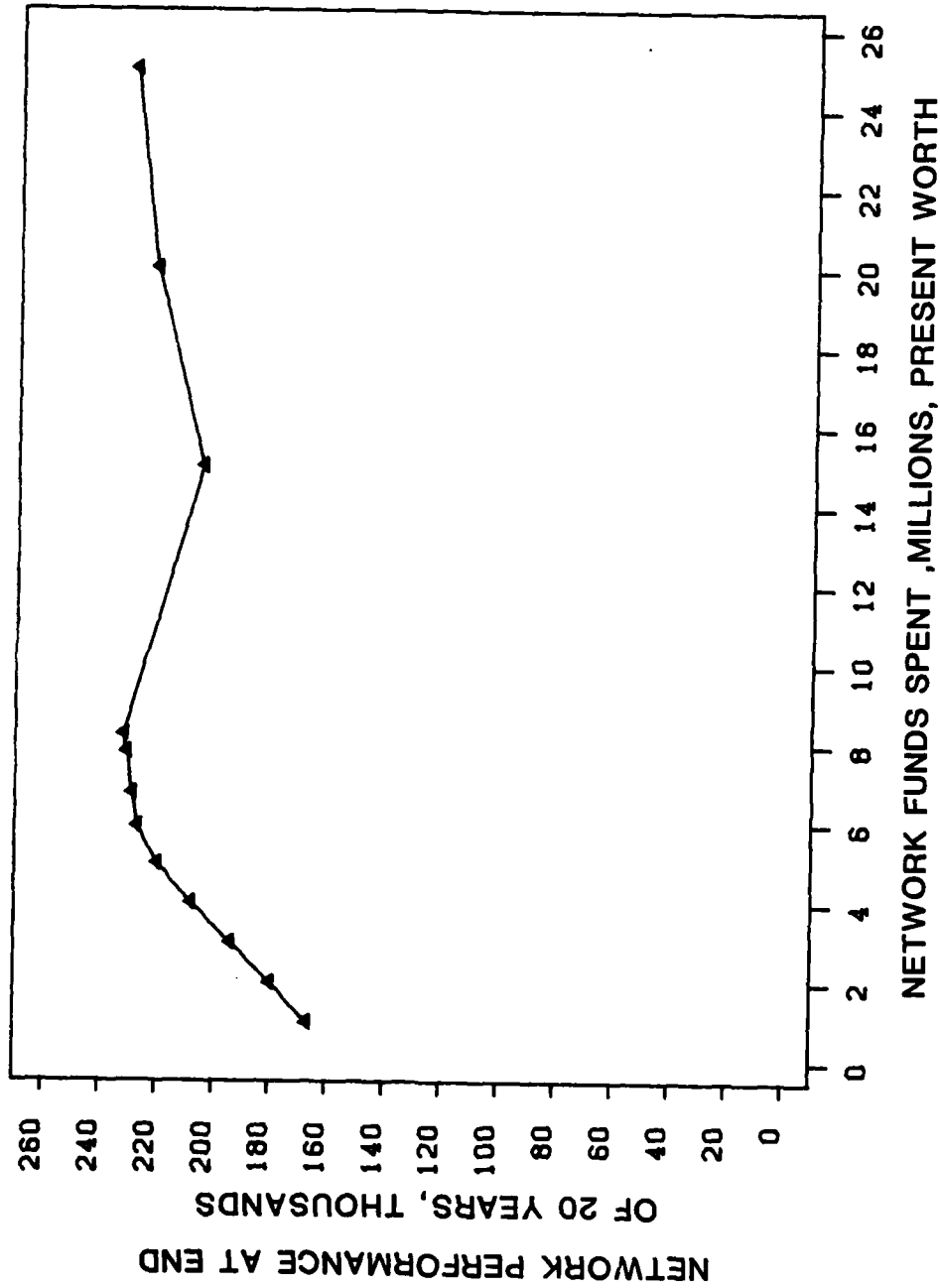


Figure 6.7 Network Performance at 20 Years Versus Network Funds Spent, McClellan AFB

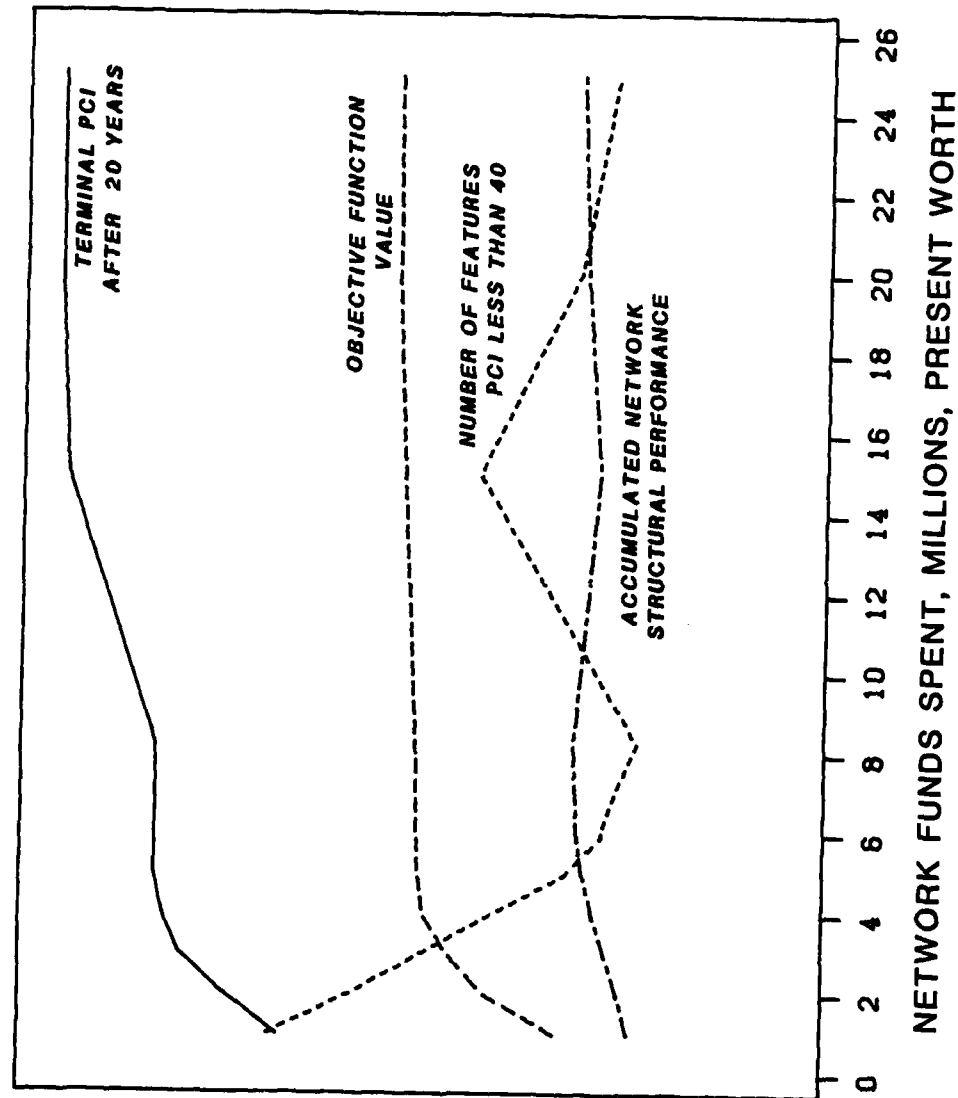


Figure 6.8 Network Consequences versus Network Funds Spent,  
McClellan AFB

a target amount to request from the funding authorities.

After the responsible agency finally decides on the network funding limit, the actual projects to be funded can be identified from an existing run of the Toyoda algorithm or a new run of the algorithm. In either case, changes to decisions made at the network level can be directly reflected to specific projects that comprise the network plan.

Just as important, with this procedure the decision makers can see the consequences of their decisions in quantifiable terms whether their decision is to reduce or increase the funding limit or to direct that certain activities be applied to specific features.

#### 6.5 Summary

This chapter discussed the application of the procedures developed in this research to an actual Air Force installation, McClellan AFB. Included is an analysis of the results with graphs/plots of the analysis data to illustrate the usefulness of the procedures. The next and last chapter includes a summary with recommendations and conclusions.

## CHAPTER 7

## SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

7.1 General

This final chapter includes a summary of the work accomplished in this research, recommendations for implementation and further research, and concluding remarks for this thesis.

7.2 Summary of Research

The goal of this research has been to develop a methodology for managing pavement networks over prolonged analysis periods. The developed methodologies are flexible and responsive to decision makers and engineers. They are also capable of reflecting changes in the management requirements (reduced budgets, special needs, etc.) on not

only a macro but also a micro scale. In other words, changes to the network analysis criteria, are reflected in specific changes in which projects are selected.

The analysis was divided into two parts, project level and network level analysis. Separate methods were devised for each, and the project level procedures were designed to provide inputs into the network level procedures. But each level of analysis can still be used independently of each other. Although the project level procedures are tailored to military airfields, the network analysis procedures are general enough to be used with most resource allocation problems, independent of whether or not they are pavement related.

The project level analysis procedures optimally select and schedule major rehabilitation activities over an extended analysis period (in this research, 20 years). The activities included are: routine maintenance, reconstruction, and overlays as detailed on Chapter 3. A computer code was written to use dynamic programming methods to select and schedule the activities over the analysis period. The program optimized the activity selection and scheduling by maximizing the structural performance of this activity for the pavement section (feature). The structural performance was characterized by the area under the utility weighted PCI (Pavement Condition Index) versus time (over the length of the analysis period) curve. The information required by the procedure is easily obtained at each Air Base and no special "pre-analysis" testing or investigation is necessary. The

output from this procedure is a feature by feature listing, selecting and scheduling the activities that maximize the structural performance during the analysis period for various levels of funding limits. These results can be used by decision makers and pavement engineers to help decide which rehabilitation activities should be considered and when to schedule them. Not only do these projects have a present worth dollar cost, but they also are given a quantified measure of the structural benefit (performance) of the project with respect to the pavement feature. The primary purpose of developing optimal projects for each feature was to generate input for the network level analysis.

Once a set of projects for a network has been developed, whether optimally by the dynamic programming procedures (recommended way) or by other methods of the engineers' choosing, the network level analysis method can be used to select the best of these projects subject to certain constraints. The network level analysis procedures select, from the group of projects submitted, those projects that maximized the sum of the user value weighted structural performance of each project. The mathematical representation of this selection process is a zero-one integer linear programming model. Although solutions to a large practical size problem normally require an impractical amount of computation time, a heuristic developed by Toyoda provides extremely good solutions.

A computer code was written to transform the dynamic programming generated results into input for the integer programming model, and then

Toyoda's method is used to select those projects that maximize the user weighted (TFW) structural performance (objective function) of the entire pavement network. Resulting from this network analysis is a list of selected projects (each related to a specific feature) that maximizes the objective function with pre-established constraints (network funding limit, etc.). The network level analysis is run for several funding levels, and a series of management information reports are generated for each.

With these reports, the consequences of selected network funding levels can quantitatively be compared. In addition, an estimate of an appropriate level of funding for the entire system can be made. These reports and subsequent analyses also reflect the consequences of network decisions with respect to specific projects affecting individual features in the pavement network. For example, the impact of a 25% reduction in network funding can easily be seen on the list of selected projects.

The entire set of developed procedures and implementing programs were developed to be amenable to further research and are adaptable to future changes (i.e., new PCI predictive equations). By having implemented them within modular computer programs, these procedures can easily incorporate future developments in pavement technology.

The information, data, and programs for this thesis research are available through Professor Michael I. Darter at 111 Talbot Laboratory,

104 South Wright Street, Urbana, IL, 61801.

### 7.3 Recommendations

During the course of this research several questions arose, most were handled adequately but others were solved in an expeditious manner. Specifically, those areas to which additional research could be addressed are:

- 1) In this work, the network level optimization objective function was defined to be the structural performance of the projects to the respective features weighted by the relative worth of the projects' affected feature to the user (TFW). This is calculated as the simple product of TFW of the feature and the total area under the utility weighted PCI versus time plot for the project. Use of this parameter for optimization needs further research to validate its adequacy. The present method is a compromise between an objective function based solely on user worth of the feature, or solely on structural performance of the project. Neither, by themselves, is correct, but which formula should be used to represent the actual combined relationship is uncertain.
- 2) The available activities to the dynamic programming algorithm should be increased from the present five (routine maintenance; reconstruction of PCC; and overlays of 2, 4, and 6 inches of



AC) to include such activities as: recycling, reconstruction with flexible pavement, undersealing and grinding, etc.. Any of these activities can be included so long as their effects to the PCI predictive equation can be quantitatively measured.

- 3) These programs and procedures along with the internal algorithms need to be validated and/or calibrated to fit the decision practices of current Air Force engineers and managers. Where opinion and judgement were necessary, those of the author were used.

#### 7.4 Conclusions

This thesis documents research conducted over the past 28 months. During the course of this work both project level and a network level analysis methodologies have been developed. This research is the first instance in which that operations research techniques (dynamic and integer programming algorithms) has been applied to optimizing the development of projects for individual airfield pavements and the selection of airfield pavement projects for an entire network of pavement sections.

A simple comparison of applying traditional manual techniques and those techniques developed in this research was made, and an application of the methods to a real Air Force base was presented. The application

to an existing Air Force base was done to show the feasibility of applying these techniques. What remains to be done is field testing these methods to incorporate changes and further validate the procedures. A more detailed comparison of the new methods and the traditional methods of pavement engineers would be difficult because the new methods provide additional insight into managing a network of pavement sections (i.e., relationship of user value and structural performance, implications of a staged decision process, etc.).

In summary, this research has developed new methods for pavement management which are implementable and which provide better pavement management than can be achieved through traditional methods. Future development of pavement management systems for both highways and airfields must begin to incorporate methods such as these and other OR techniques in order to assure maximal pavement performance under scarcities of resources and money.

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## VITA

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